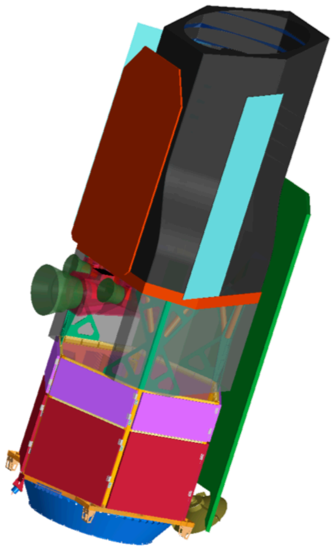
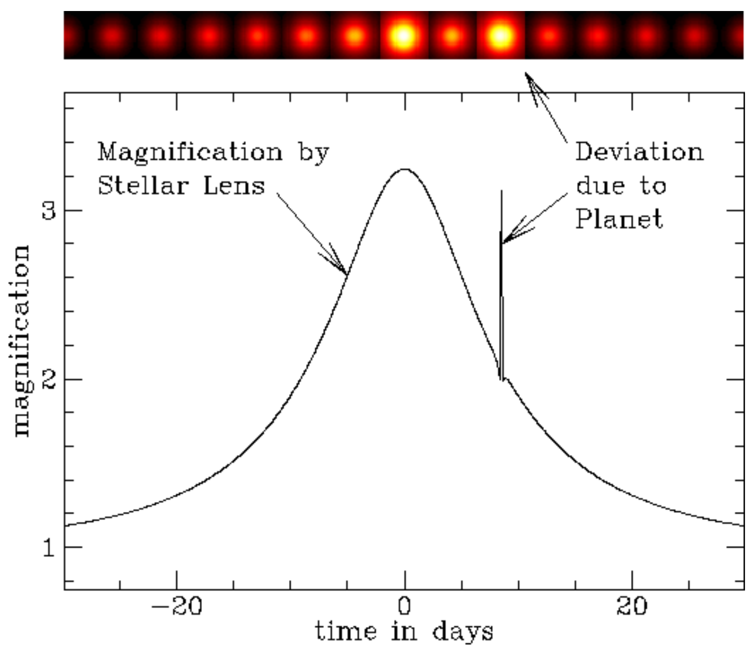
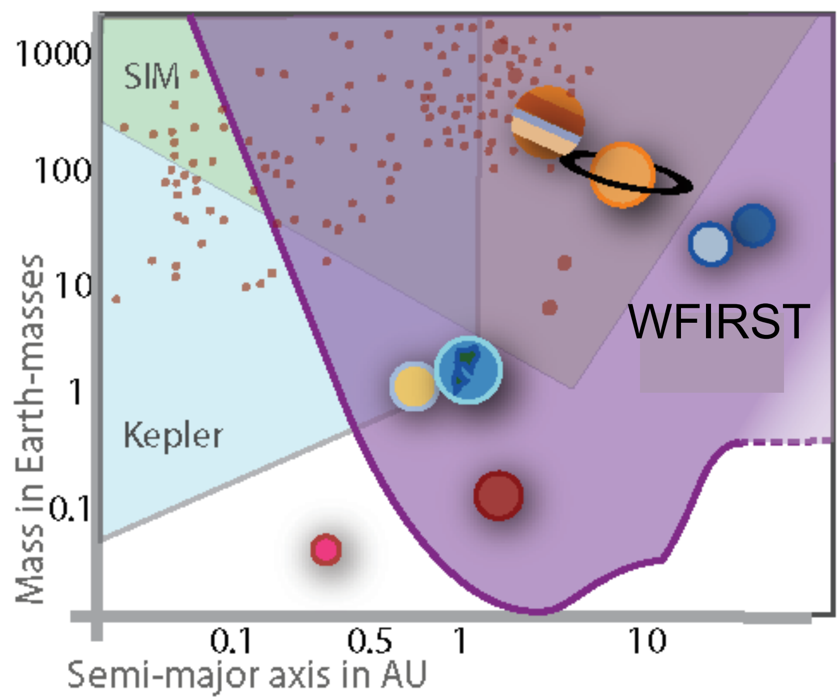


The WFIRST Microlensing Exoplanet Survey:

Basic Concepts and Figure of Merit

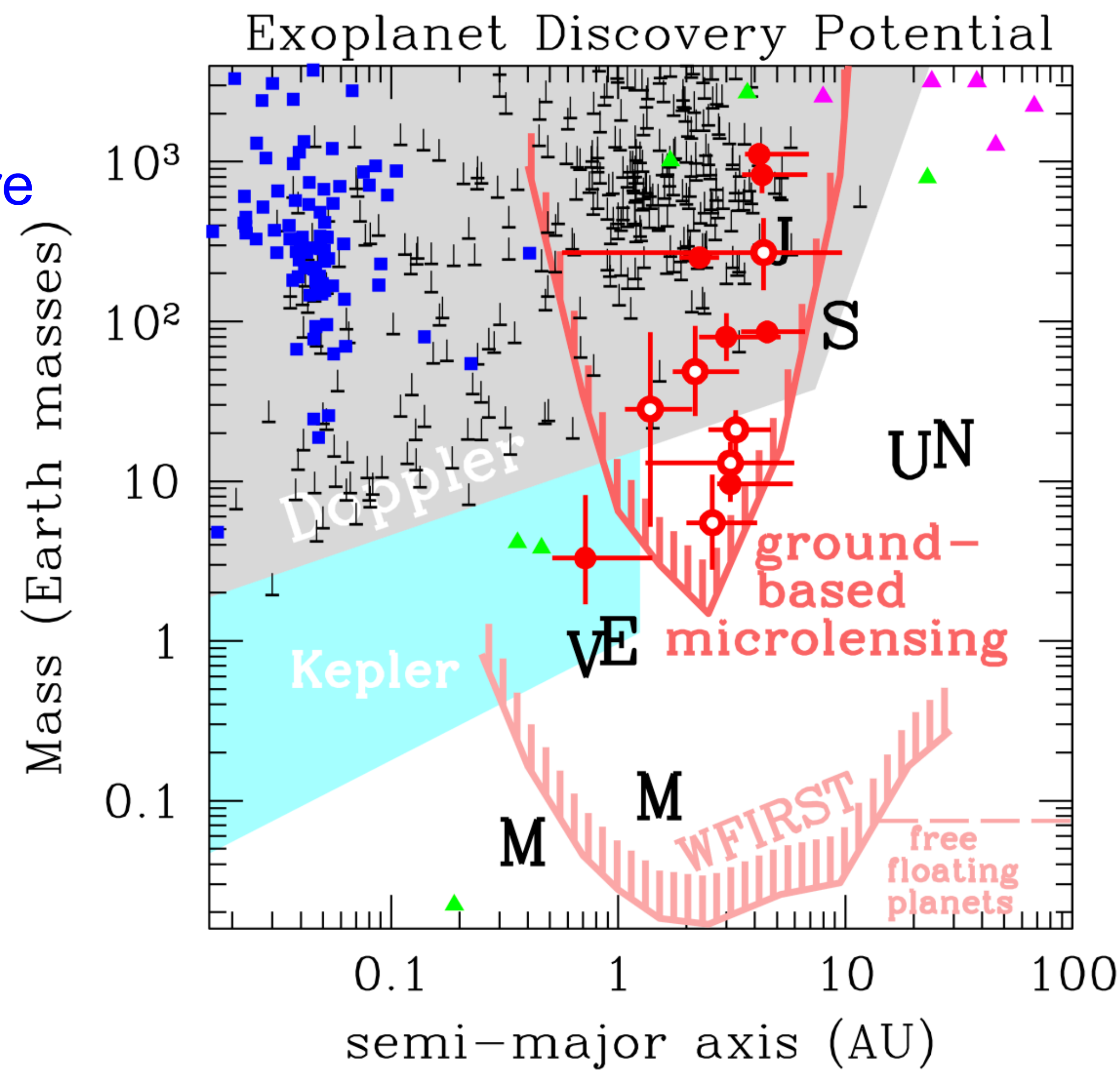
David Bennett
University of Notre Dame





Planet Discoveries by Method

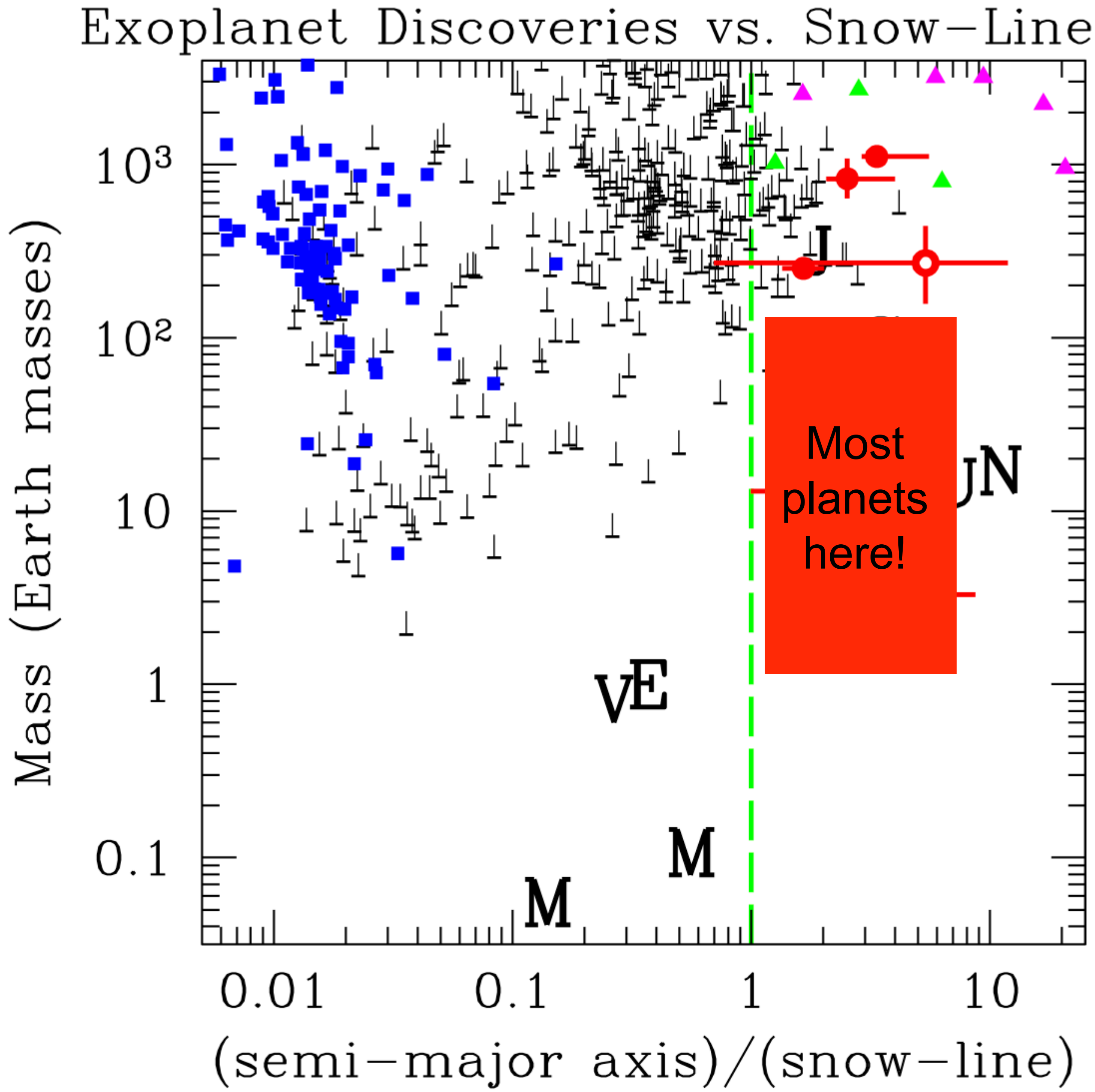
- ~400 Doppler discoveries in black
- Transit discoveries are blue squares
- Gravitational microlensing discoveries in red
  - cool, low-mass planets
- Direct detection, and timing are magenta and green triangles



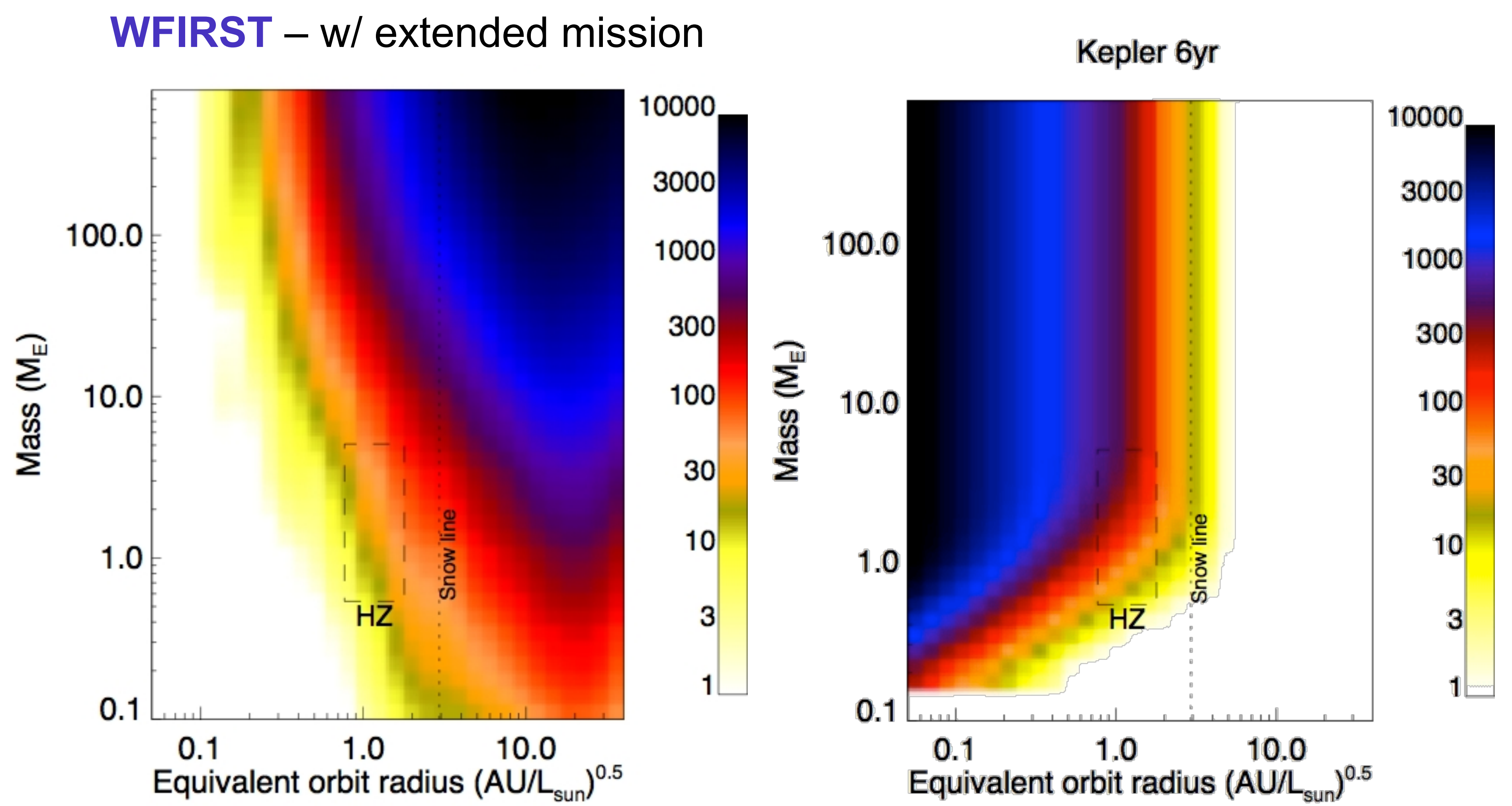
Planet mass vs. semi-major axis/snow-line

- “snow-line” defined to be 2.7 AU ($M/M_{\odot}$)
  - since L∝ M^2 during planet formation
- Microlensing discoveries in **red.**
- Doppler discoveries in black
- Transit discoveries shown as blue circles

- Super-Earth planets beyond the snow-line appear to be the most common type yet discovered

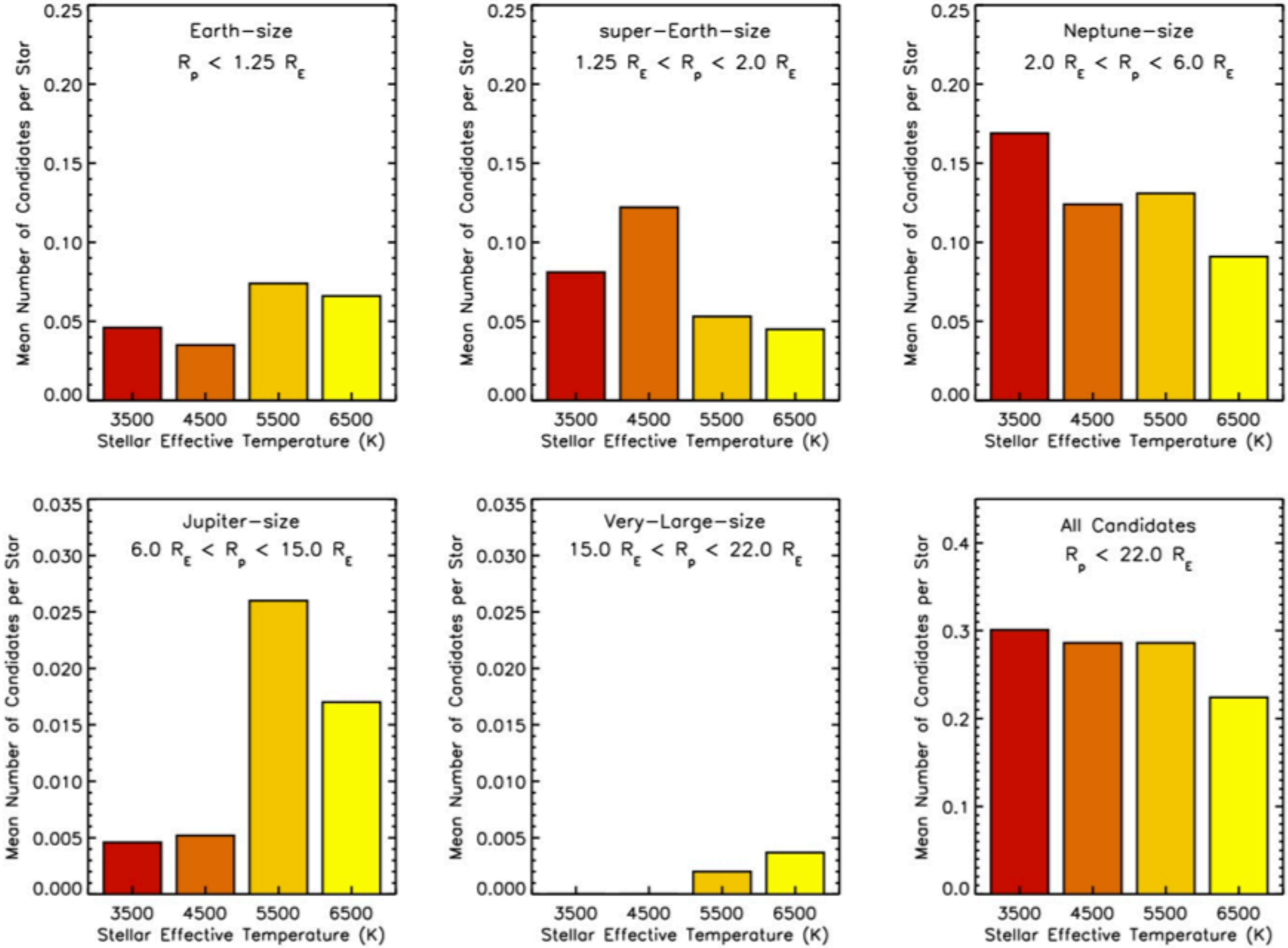


WFIRST vs. Kepler

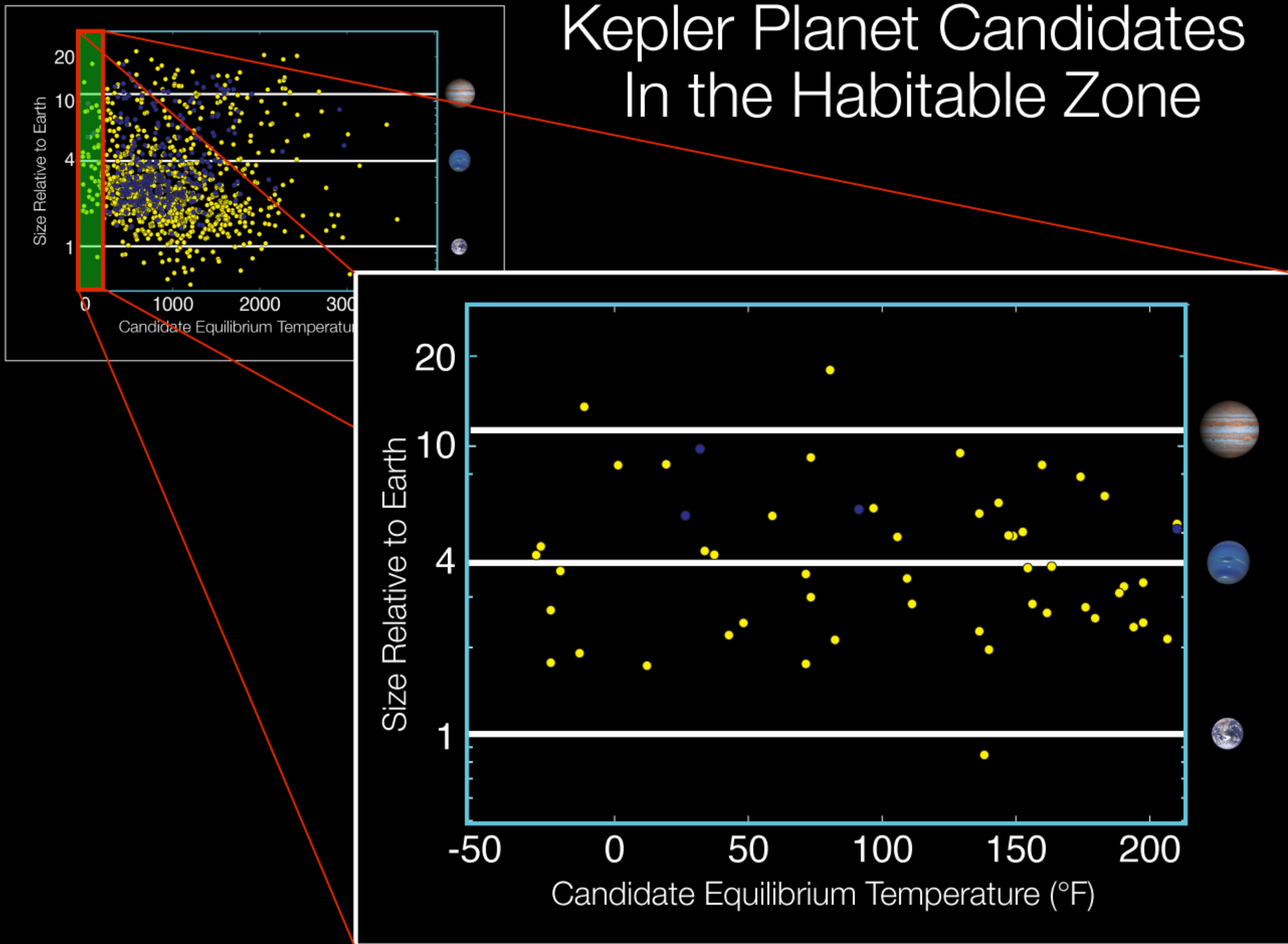


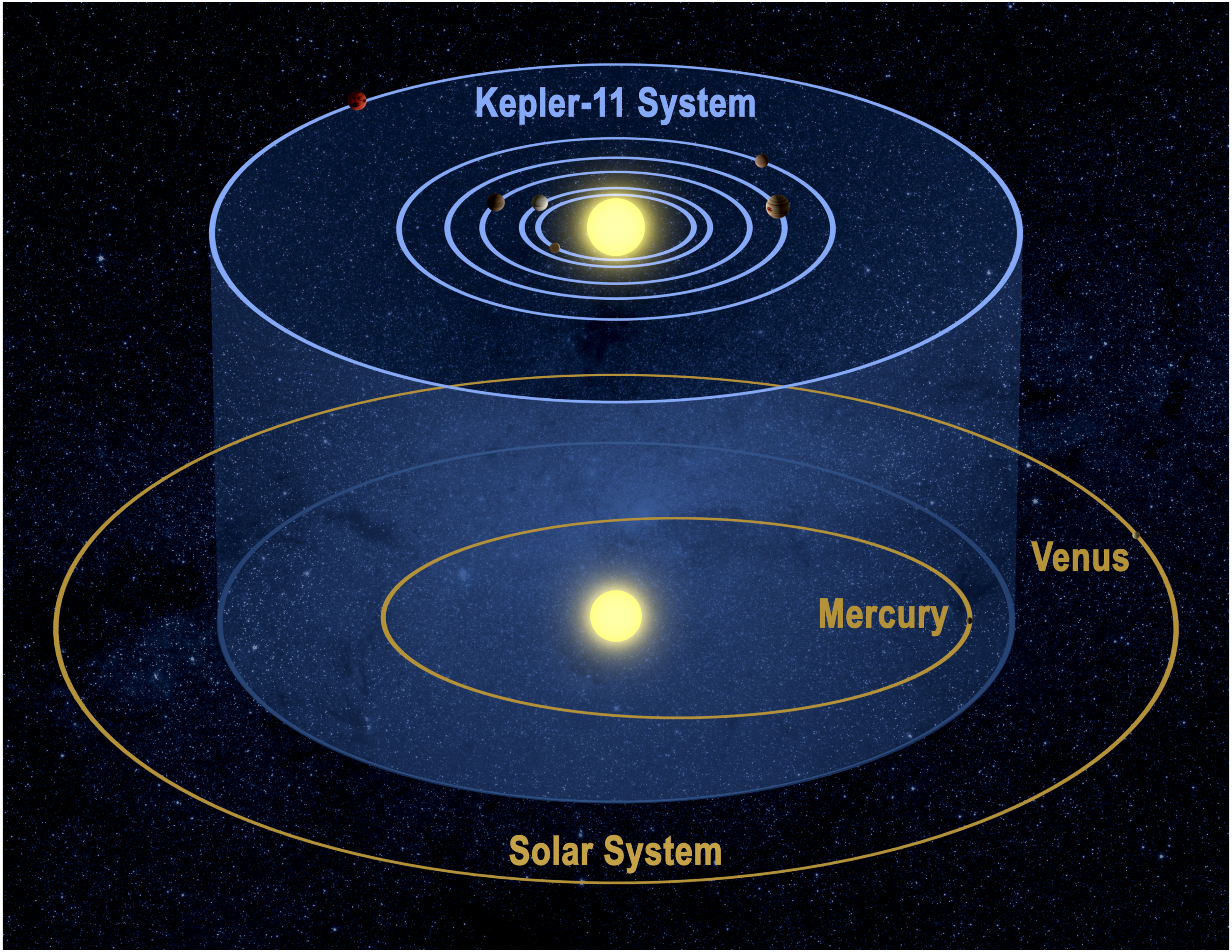
Figures from B. MacIntosh of the ExoPlanet Task Force

Kepler: 2 Feb. 2011:1200 Planet Candidates



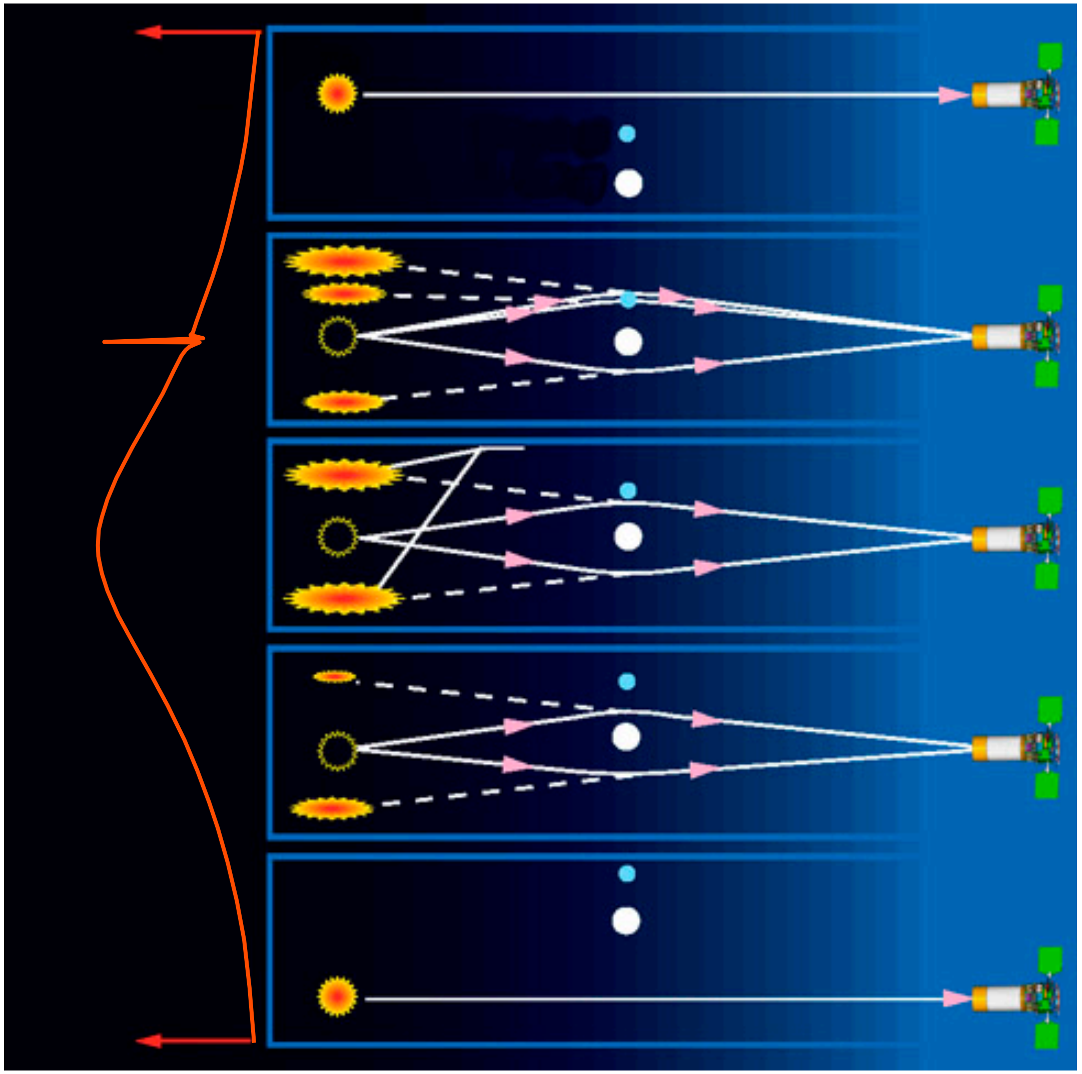
Kepler Planet Candidates In the Habitable Zone




Kepler-11 System
Venus
Mercury
Solar System

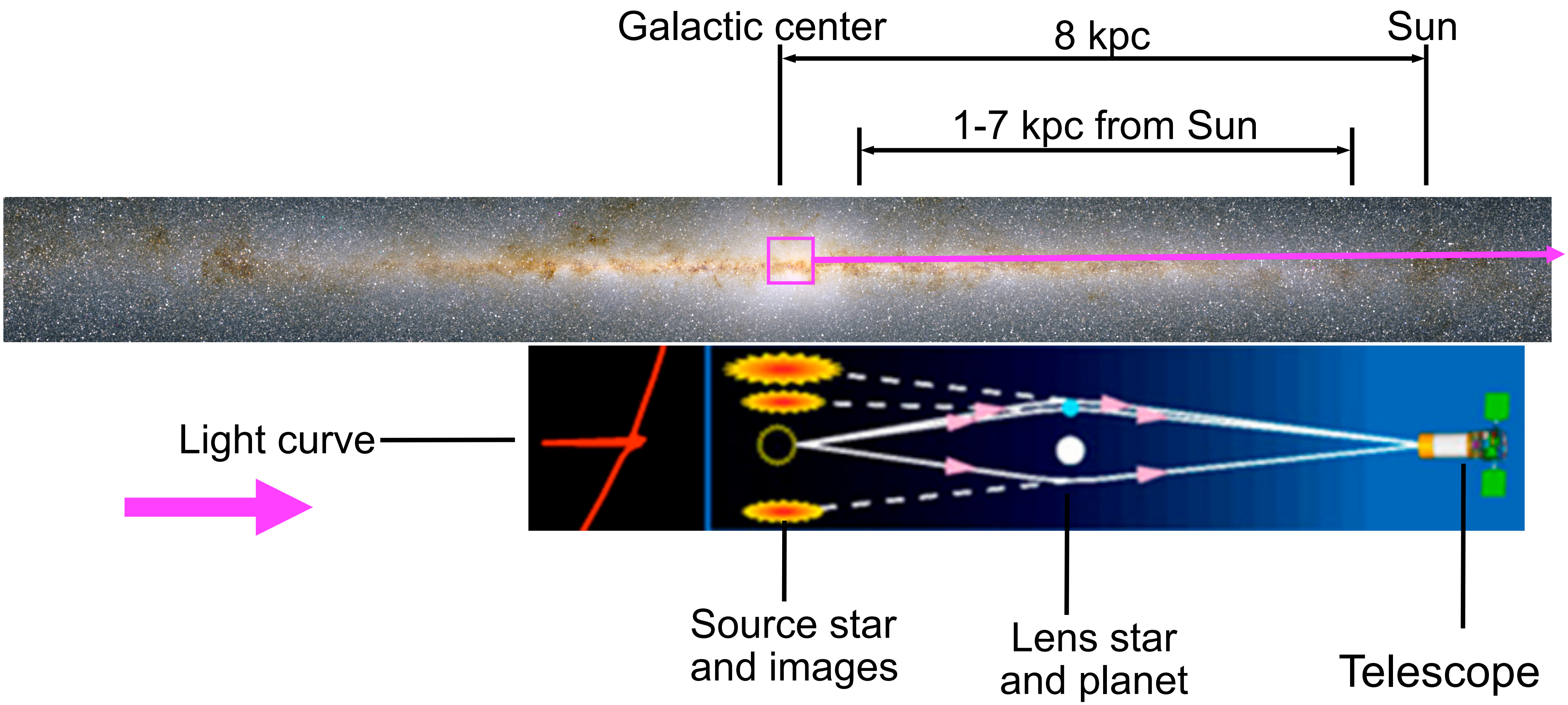
The Physics of Microlensing

- Foreground "lens" star + planet bend light of "source" star
- Multiple distorted images
  - Only total brightness change is observable
- Sensitive to planetary mass
- Low mass planet signals are rare – not weak
- Stellar lensing probability ~a few $\times 10^{-6}$
  - Planetary lensing probability ~0.001-1 depending on event details
- Peak sensitivity is at 2-3 AU: the Einstein ring radius, R_E



Key Fact: $1\ \mathrm{AU} \approx \sqrt{R_{Sch} R_{GC}} = \sqrt{\dfrac{2GM}{c^2} R_{GC}}$

Microlensing Target Fields are in the Galactic Bulge

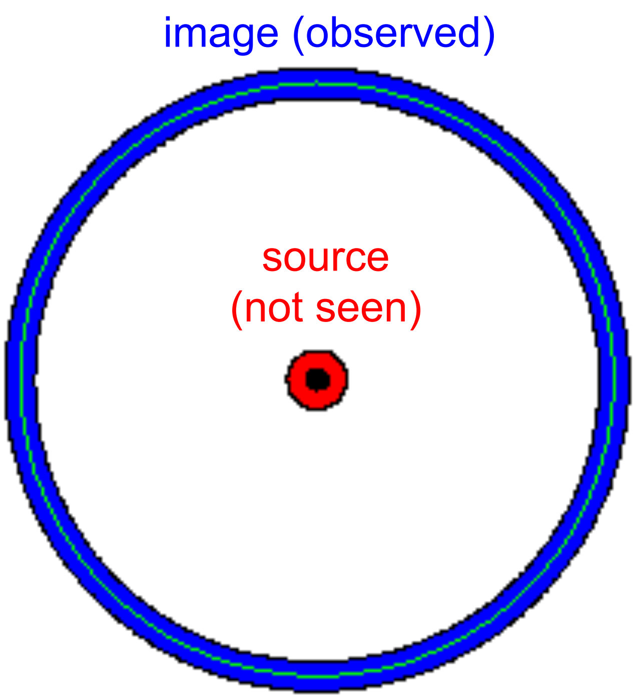


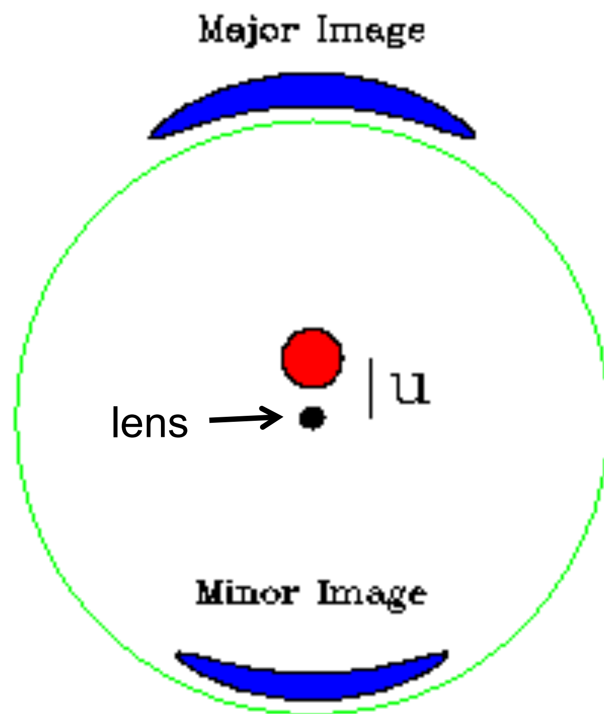
10s of millions of stars in the Galactic bulge in order to detect planetary companions to stars in the Galactic disk and bulge.

Why Space-based Microlensing?

- Microlensing requires extremely crowded fields
- Source stars only resolvable from space
- Ground-based surveys need high lensing magnification to resolve most source stars
  - Limits sensitivity to near the Einstein ring
  - Space-based microlensing sensitive from 0.5 AU - ∞
- Space-based microlensing allows detection of most lens stars
  - Allows direct determination of star and planet masses
- Simulations from Bennett & Rhie (2002)
- Basic results confirmed by independent simulations (Gaudi)
- MPF Discovery proposal (2006) -> WFIR T Wide-Field Infra-Red Survey Telescope

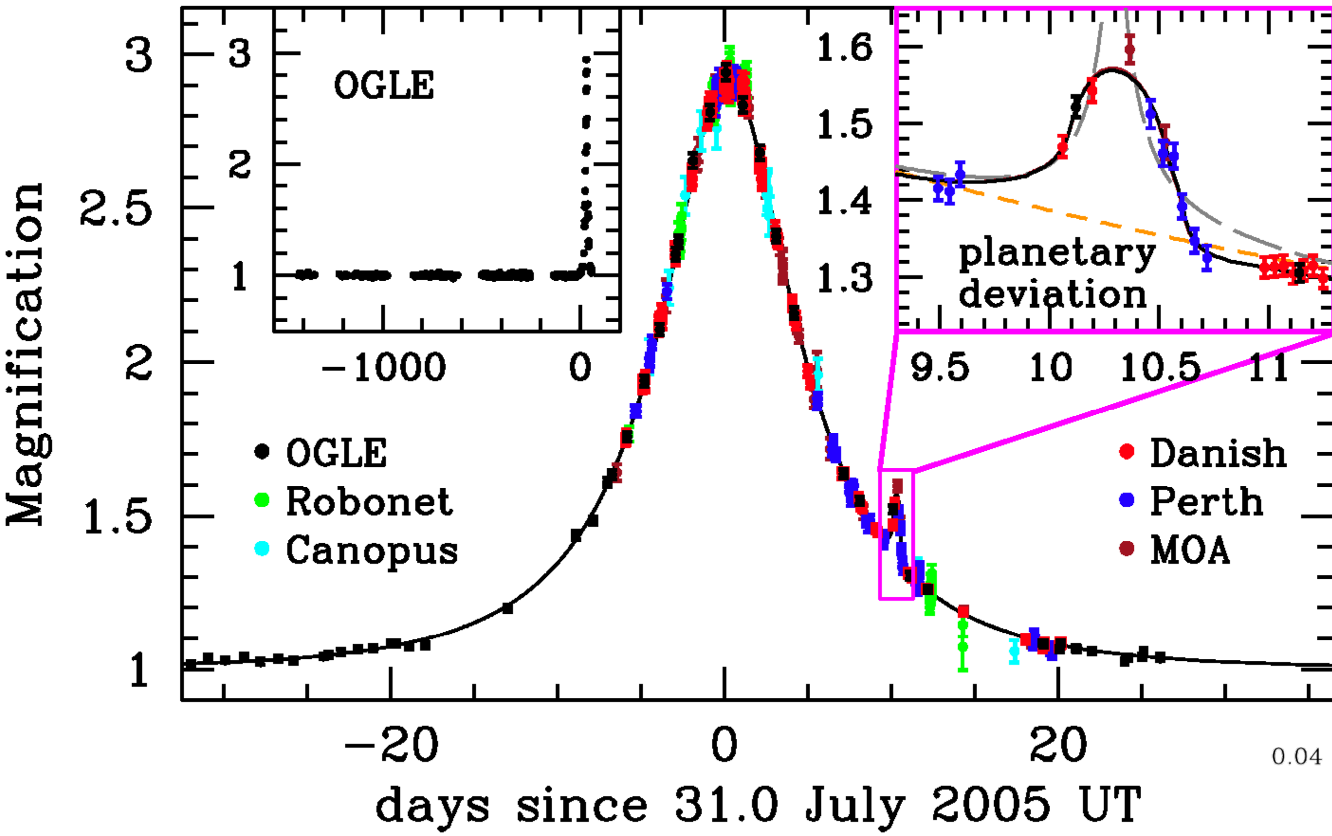
Gravitational Lensing (Einstein 1936)



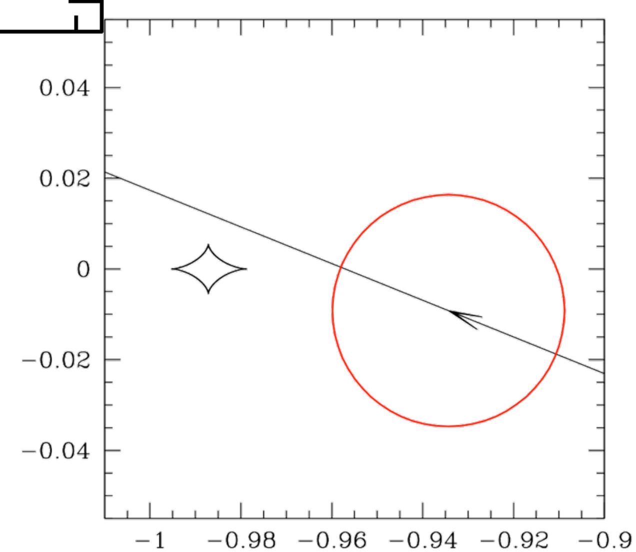


When source is distant, we see distorted, magnified images. If the alignment is perfect, we see an "Einstein Ring". Einstein said, "there is no great chance of observing this effect". The probability at any one time is ~1 in a million, but we see ~800 per year.

OGLE-2005-BLG-390Lb - “lowest” mass exoplanet



A 5.5 $M_{\oplus}$ planet discovered by microlensing: OGLE-2005-BLG-390Lb. The lowest mass planet discovered when announced in 2006.

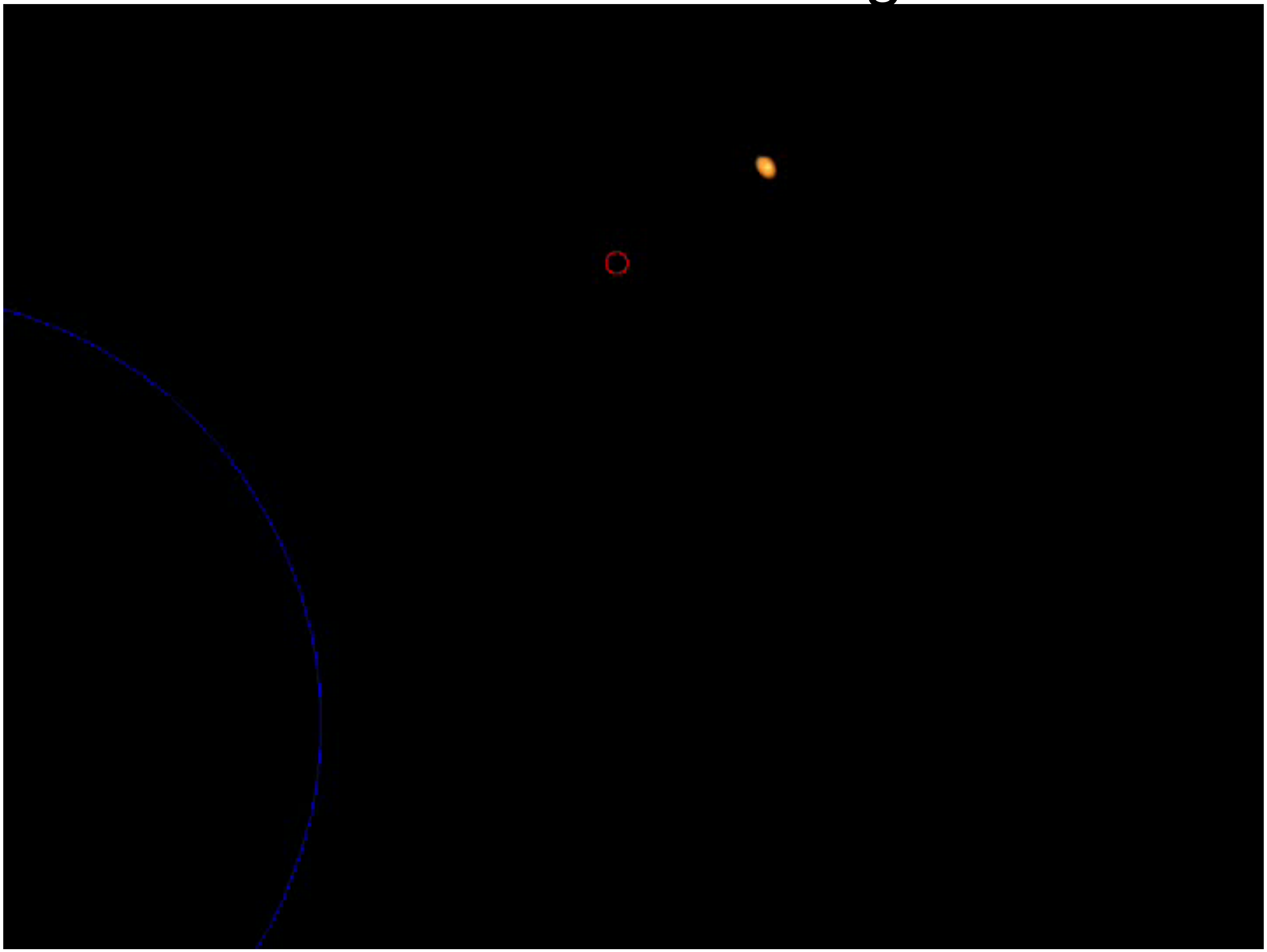


Source passes over caustic => significant finite source effect and clear measurement of t_*

Giant source star means lens star detection will be difficult

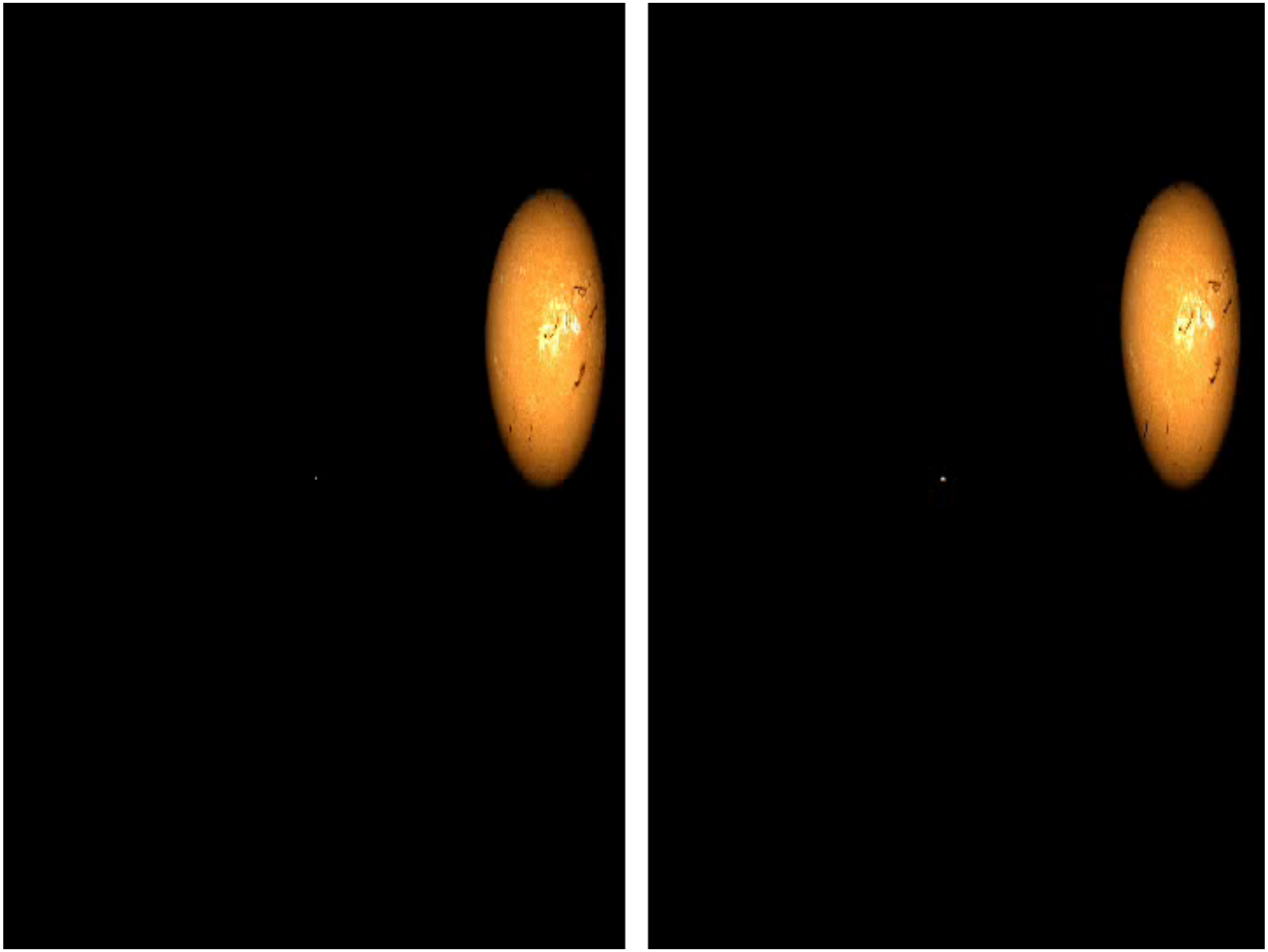
PLANET, OGLE & MOA Collaborations

OGLE-2005-BLG-390Lb at high resolution



- Simulated view from 10,000 km aperture space telescope
- H-α filter Solar images generate cool videos!

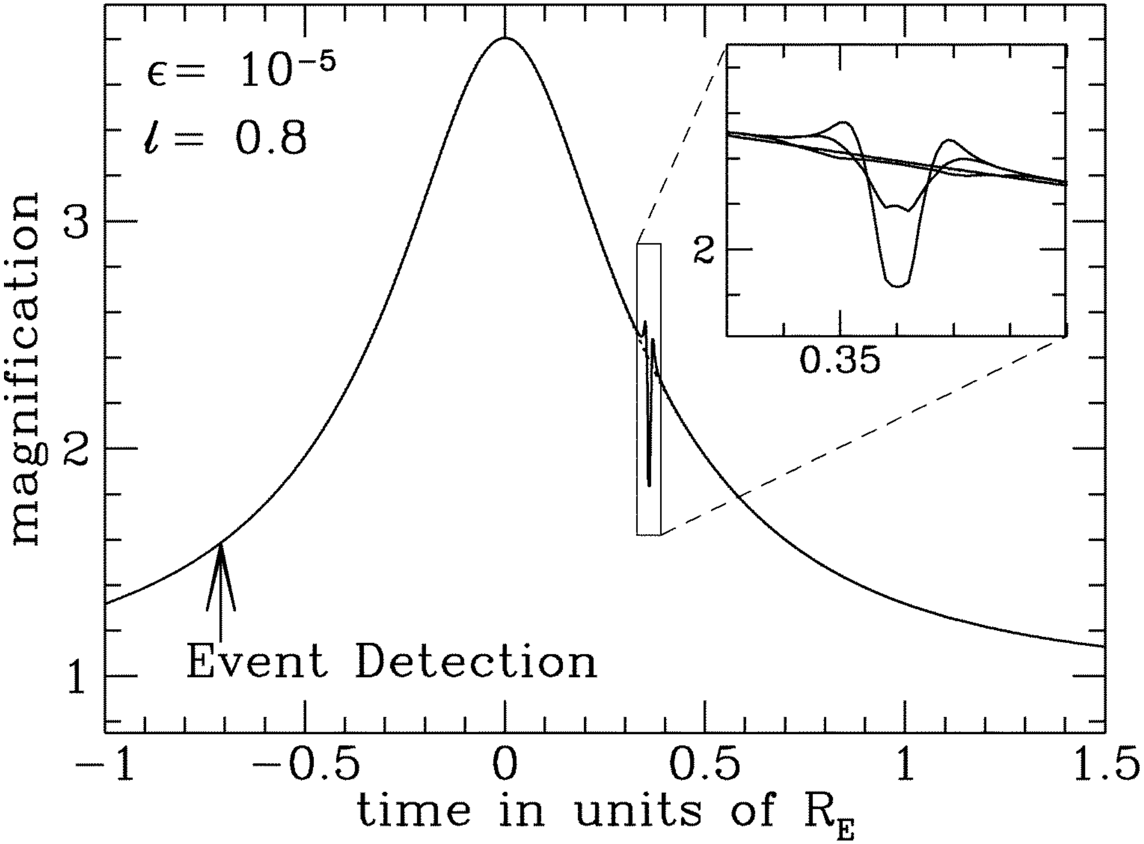
OGLE-2005-BLG-390Lb at high resolution



5.5 Earth-mass planet vs. 16.5 Earth-mass planet.

Only the total image area is observable. 5.5 Earth-mass is near limit for giant source.

How Low Can We Go?



(Bennett & Rhie 1996)

Limited by Source Size

angular Einstein radius

$$\boxed{\theta_E \approx \mu\text{as}\left(\frac{M_p}{M_\oplus}\right)^{1/2}}$$

$$\updownarrow$$

$$\boxed{\theta_* \approx \mu\text{as}\left(\frac{R_*}{R_\odot}\right)}$$

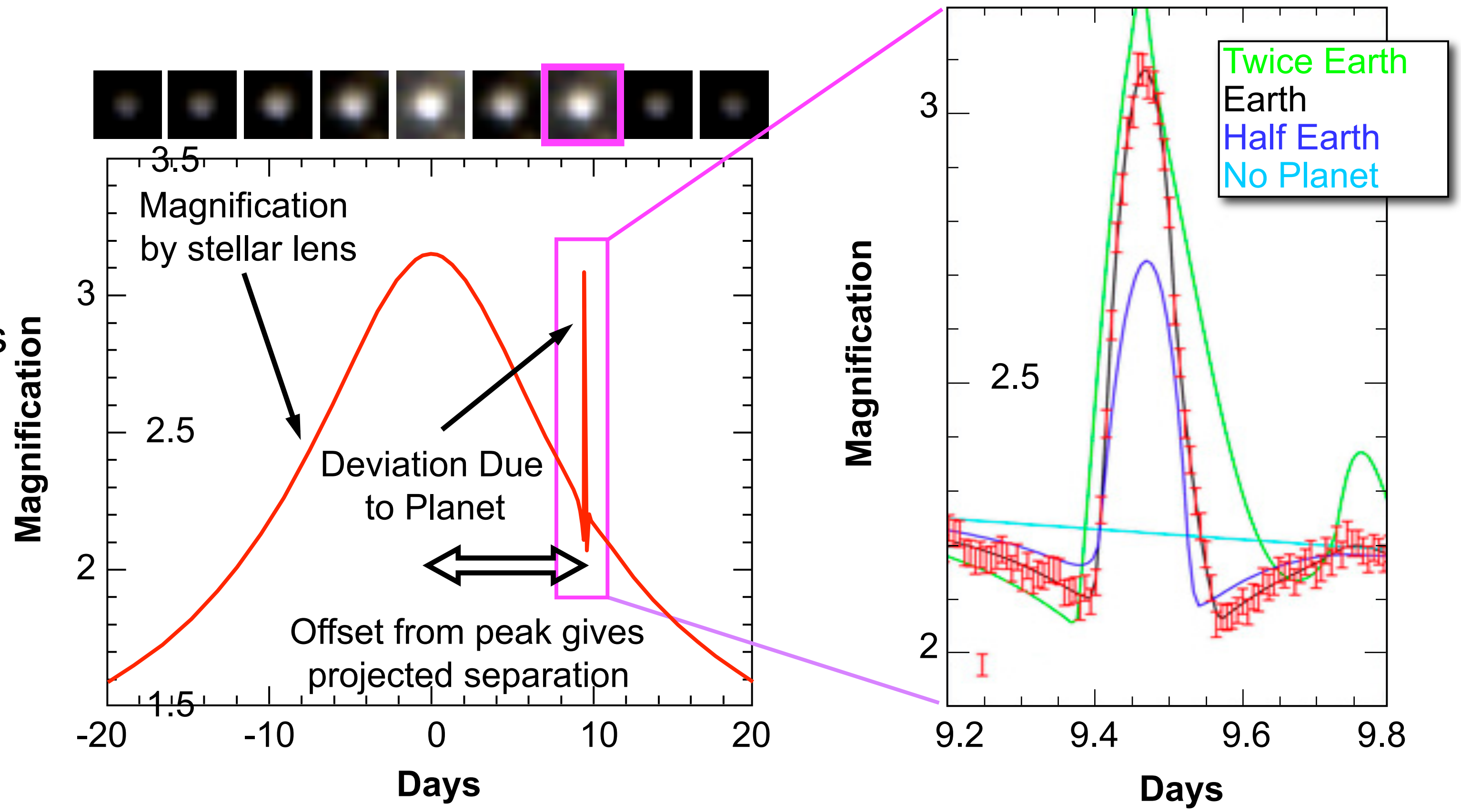
angular source star radius

For $\theta_E \geq \theta_*$:
low-mass planet signals are rare and brief, but not weak

Mars-mass planets detectable
if solar-type sources can be monitored!

Extraction of Exoplanet Signal

Time-series photometry is combined to uncover light curves of background source stars being lensed by foreground stars in the disk and bulge.



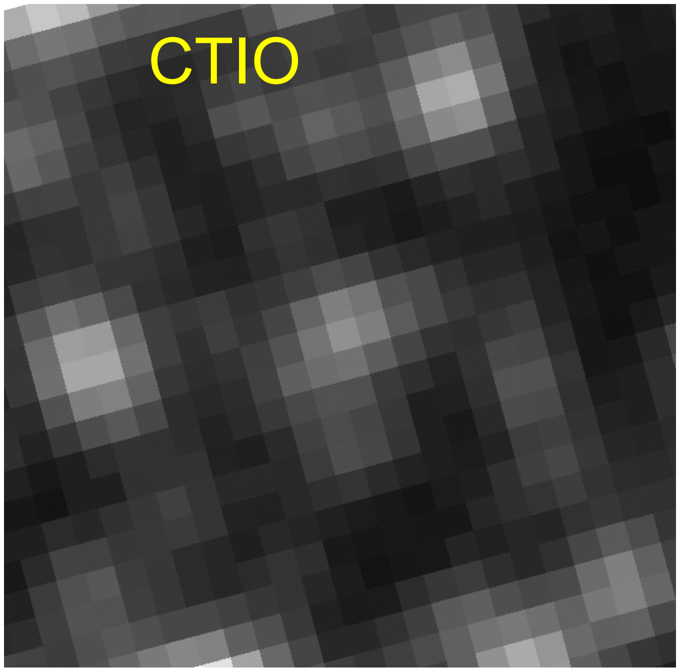
Planets are revealed as short-duration deviations from the smooth, symmetric magnification of the source due to the primary star.

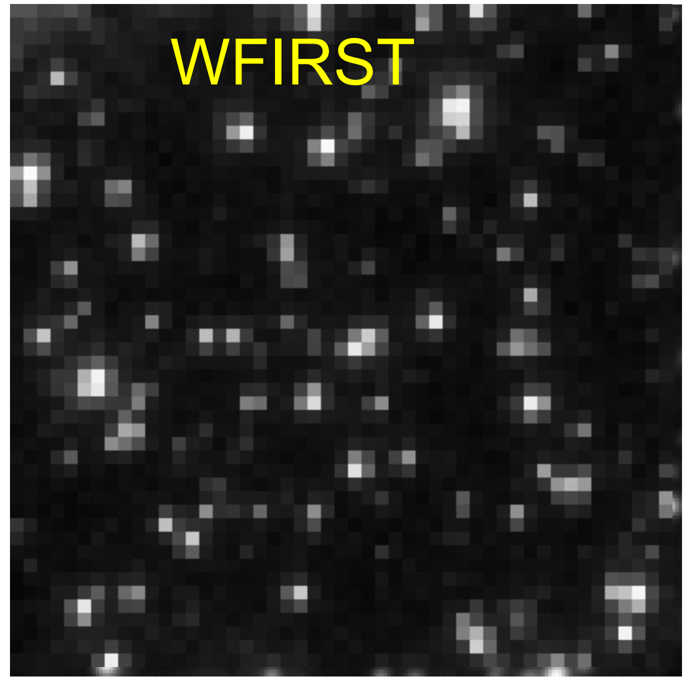
Detailed fitting to the photometry yields the parameters of the detected planets.

Exoplanets via Gravitational Microlensing

- 11 published discoveries and a similar number in preparation
- Sensitive to low-mass planets at a few AU
- Sensitive to planetary mass
- Planetary signal strength independent of mass
  - if $M_{planet} > 0.1\ M_{\oplus}$ for main sequence source stars
  - low-mass planet signals are brief and rare
- ~10% photometric variations
  - required photometric accuracy demonstrated
- Prime sensitivity near Einstein radius at ~2-3 AU
  - High sensitivity near “snow line” - important for testing planet formation theories
- M_{planet}/M_*, separation/(Einstein radius) from light curve
- follow-up observations measure M_{planet} , M_*
- Potentially finds free-floating planets, too

Ground-based confusion, space-based resolution





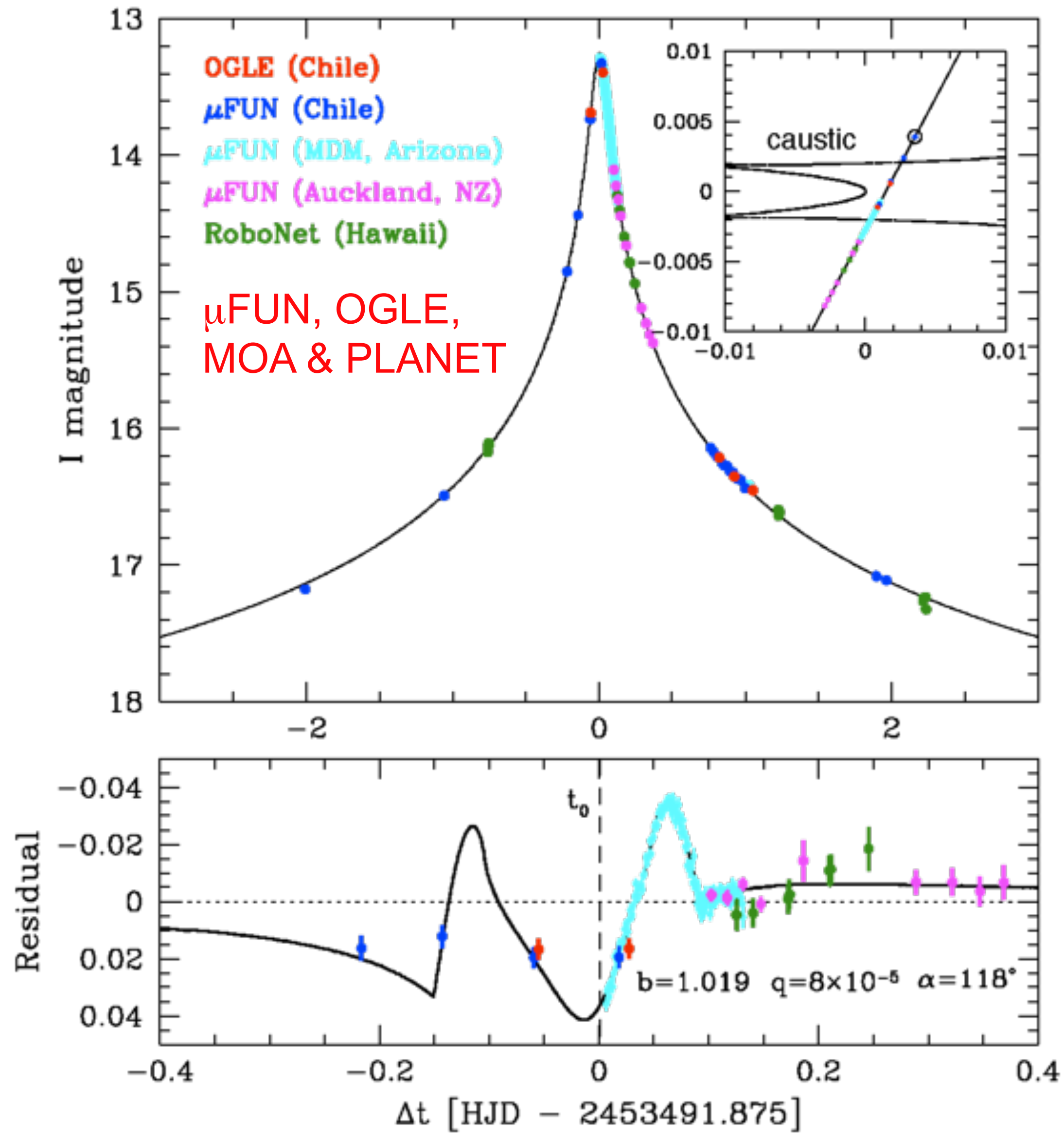
- Space-based imaging needed for high precision photometry of main sequence source stars (at low magnification) and lens star detection
- High Resolution + large field + 24hr duty cycle => Microlensing Planet Finder (MPF)
- Space observations needed for sensitivity at a range of separations and mass determinations

High-magnification: Low-mass planets

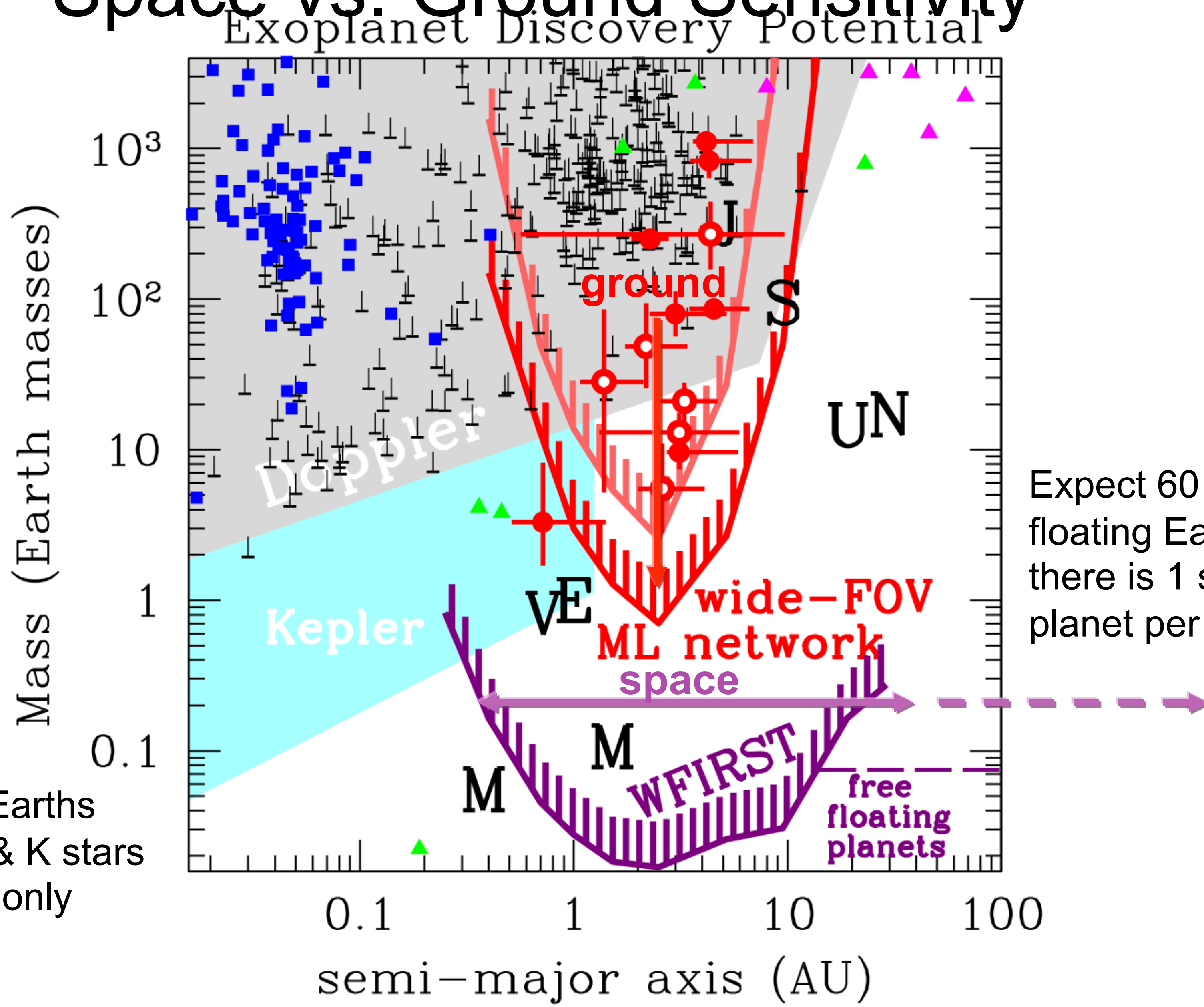
OGLE-2005-BLG-169Lb

- Detection of a ~13 $M_\oplus$ planet in a A_{max}= 800 event
- Caustic crossing signal is obvious when light curve is divided by a single lens curve.
- Detection efficiency for ~10 $M_\oplus$ planets is << than for Jupiter-mass planets

- Competing models with an Earth-mass planet had a signal of similar amplitude
- So, an Earth-mass planet could have been detected in this event!



Space vs. Ground Sensitivity



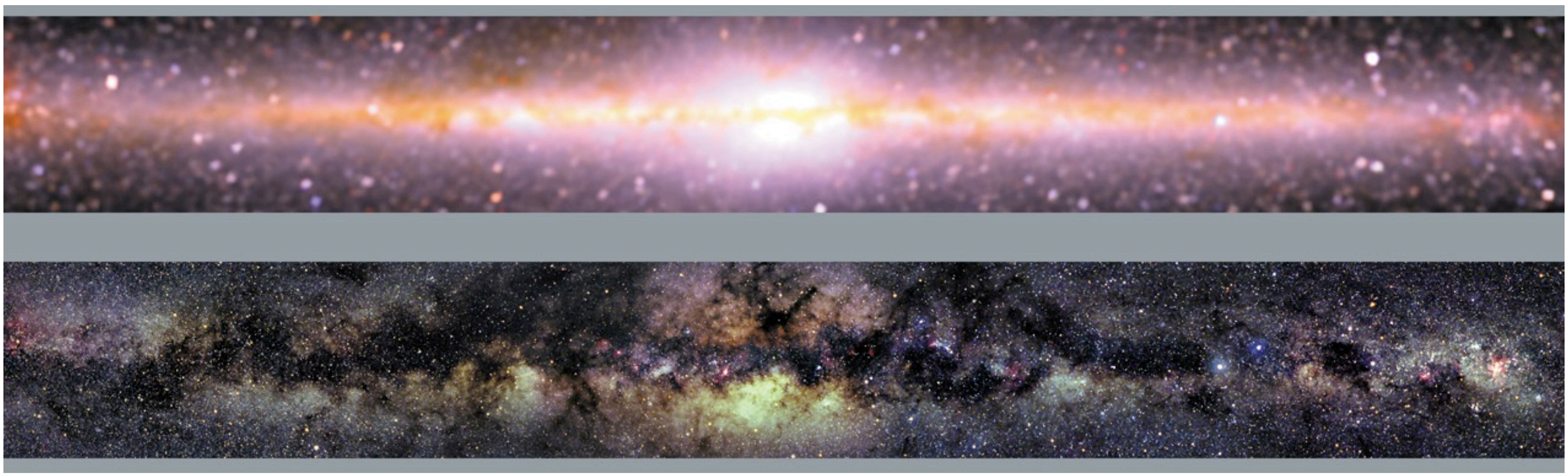
Expect 60 free-floating Earths if there is 1 such planet per star

Habitable Earths orbiting G & K stars accessible only from space

Infrared Observations Are Best

The central Milky Way:

near infrared

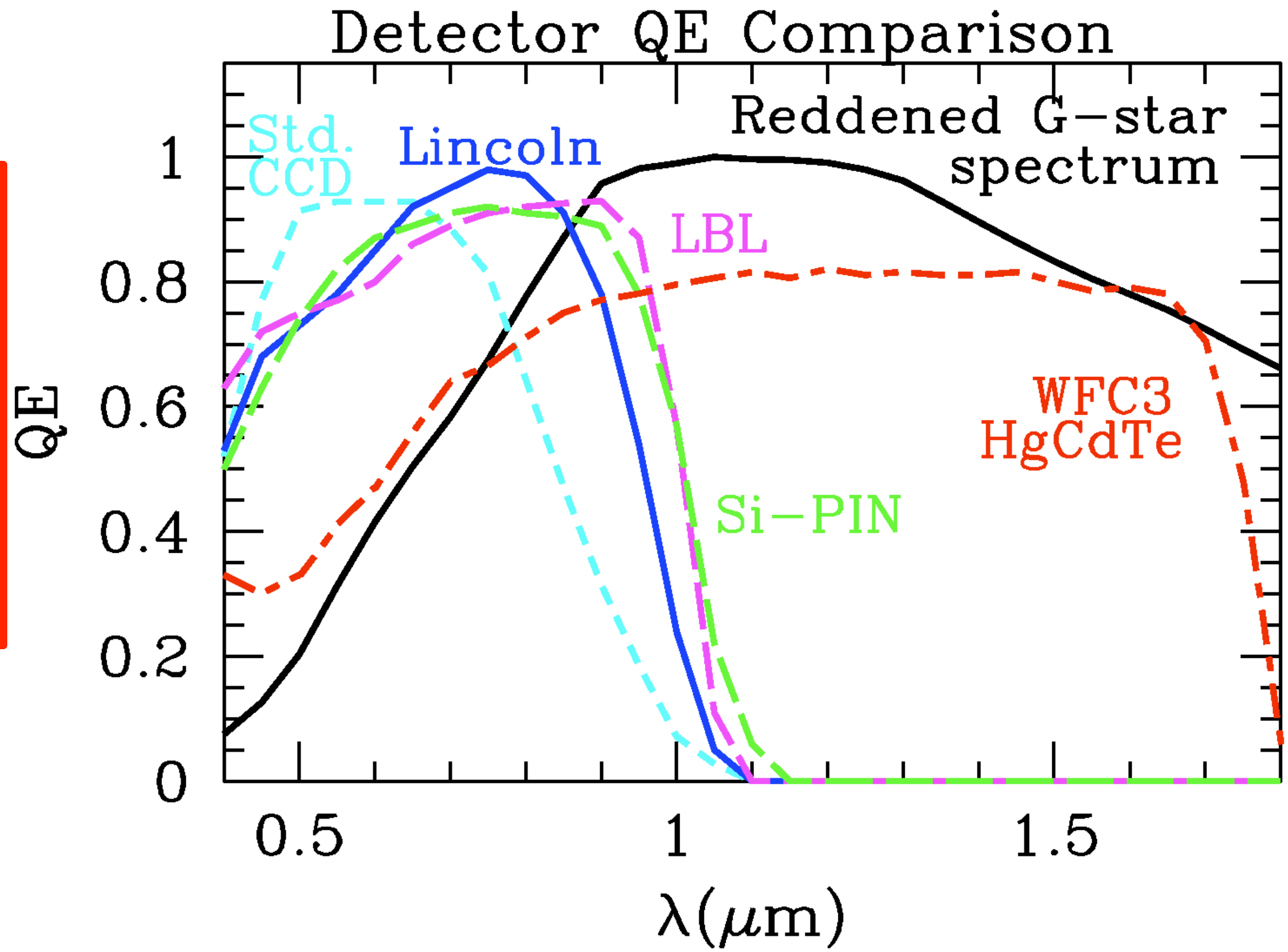


optical

Dust obscures the best microlensing fields toward the center of the Galaxy

Detector Sensitivity

An IR space microlensing survey is 5× more sensitive than an optical one.

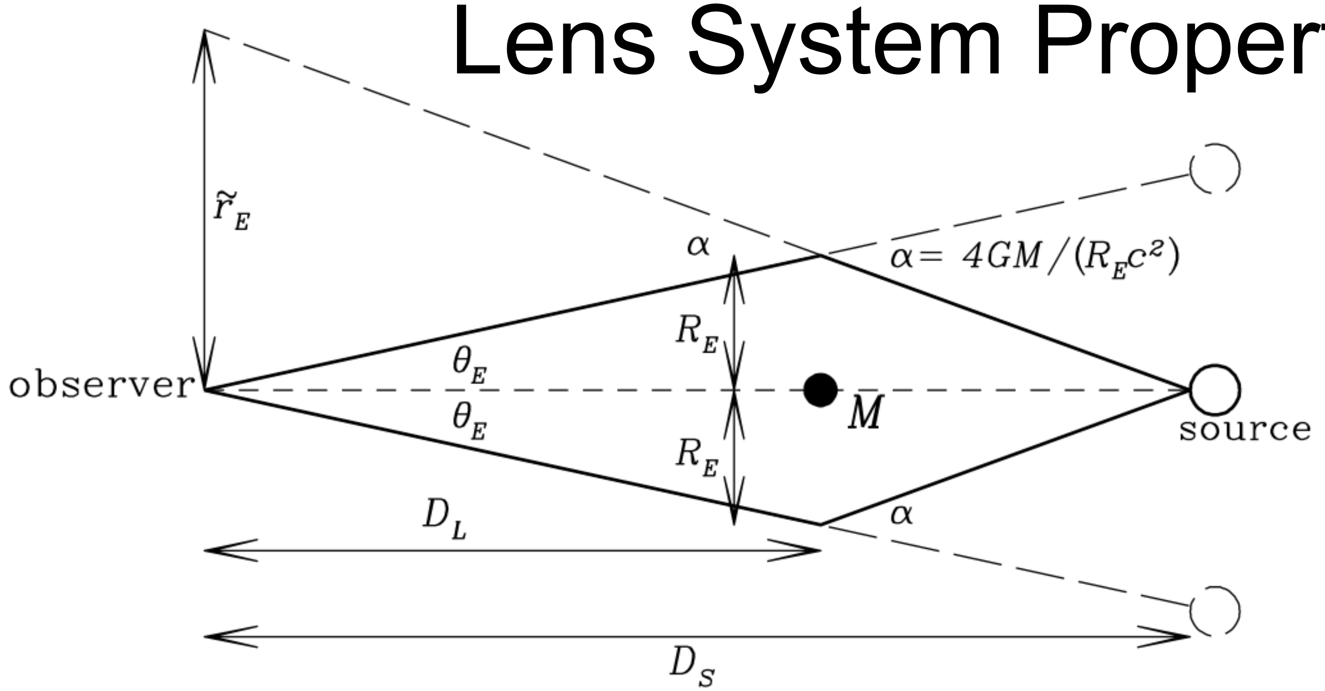


Spectrum of a reddened source star is compared to the QE curves of CCDs and Si detectors. The HgCdTe detectors developed for HST's WFC3 instrument can detect twice as many photons as the most IR sensitive CCDs.

Lens System Properties

- For a single lens event, 3 parameters (lens mass, distance, and velocity) are constrained by the Einstein radius crossing time, t_E
- There are two ways to improve upon this with light curve data:
  - Determine the angular Einstein radius : $\theta_E = \theta_* t_E / t_* = t_E \mu_{rel}$ where θ_* is the angular radius of the star and μ_{rel} is the relative lens-source proper motion
  - Measure the projected Einstein radius, $\tilde{r}_E$, with the microlensing parallax effect (due to Earth's orbital motion).

Lens System Properties



- Einstein radius : $\theta_E = \theta_* t_E / t_*$ and projected Einstein radius, $\tilde{r}_E$
  - θ_* = the angular radius of the star
  - $\tilde{r}_E$ from the microlensing parallax effect (due to Earth's orbital motion).

$$R_E = \theta_E D_L, \text{ so } \alpha = \frac{\tilde{r}_E}{D_L} = \frac{4GM}{c^2 \theta_E D_L}. \text{ Hence } M = \frac{c^2}{4G} \theta_E \tilde{r}_E$$

Finite Source Effects & Microlensing Parallax Yield Lens System Mass

- If only θ_E or $\tilde{r}_E$ is measured, then we have a mass-distance relation.
- Such a relation can be solved if we detect the lens star and use a mass-luminosity relation
  - This requires space-based resolution
  - Observer relative proper motion to rule out false positives
- With θ_E, $\tilde{r}_E$, and lens star brightness, we have more constraints than parameters

mass-distance relations:

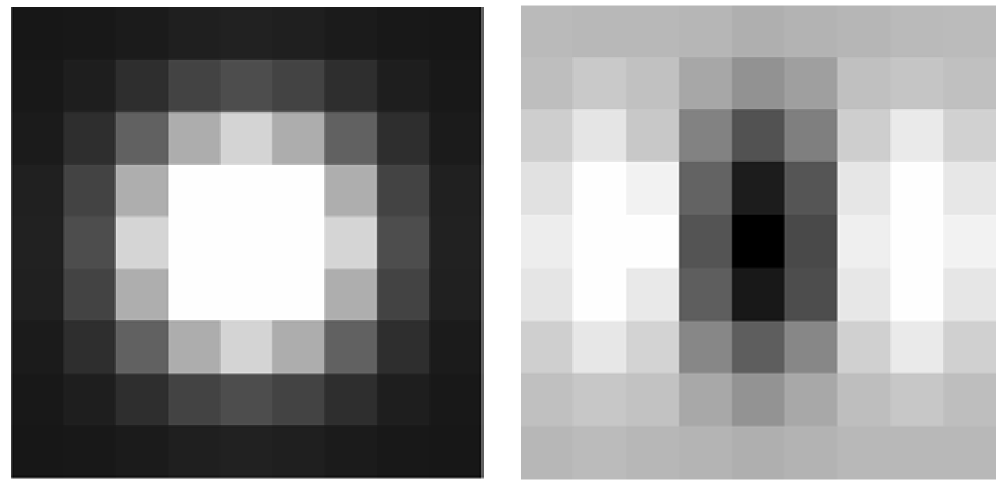
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E \theta_E$$

Lens Star Detection in **WFIRST** Images

- The typical lens-source relative proper motion is μ_{rel}~ 5 mas/yr
- This gives a total motion of >0.05 pixels over 3 years
- This is directly detectable in co-added MPF images due to MPF's stable PSF and large number of images of each of the target fields.
- μ_{rel} is also determined from the light curve fit.
- A color difference between the source and lens stars provides a signal of μ_{rel} in the color dependence of the source+lens centroid position

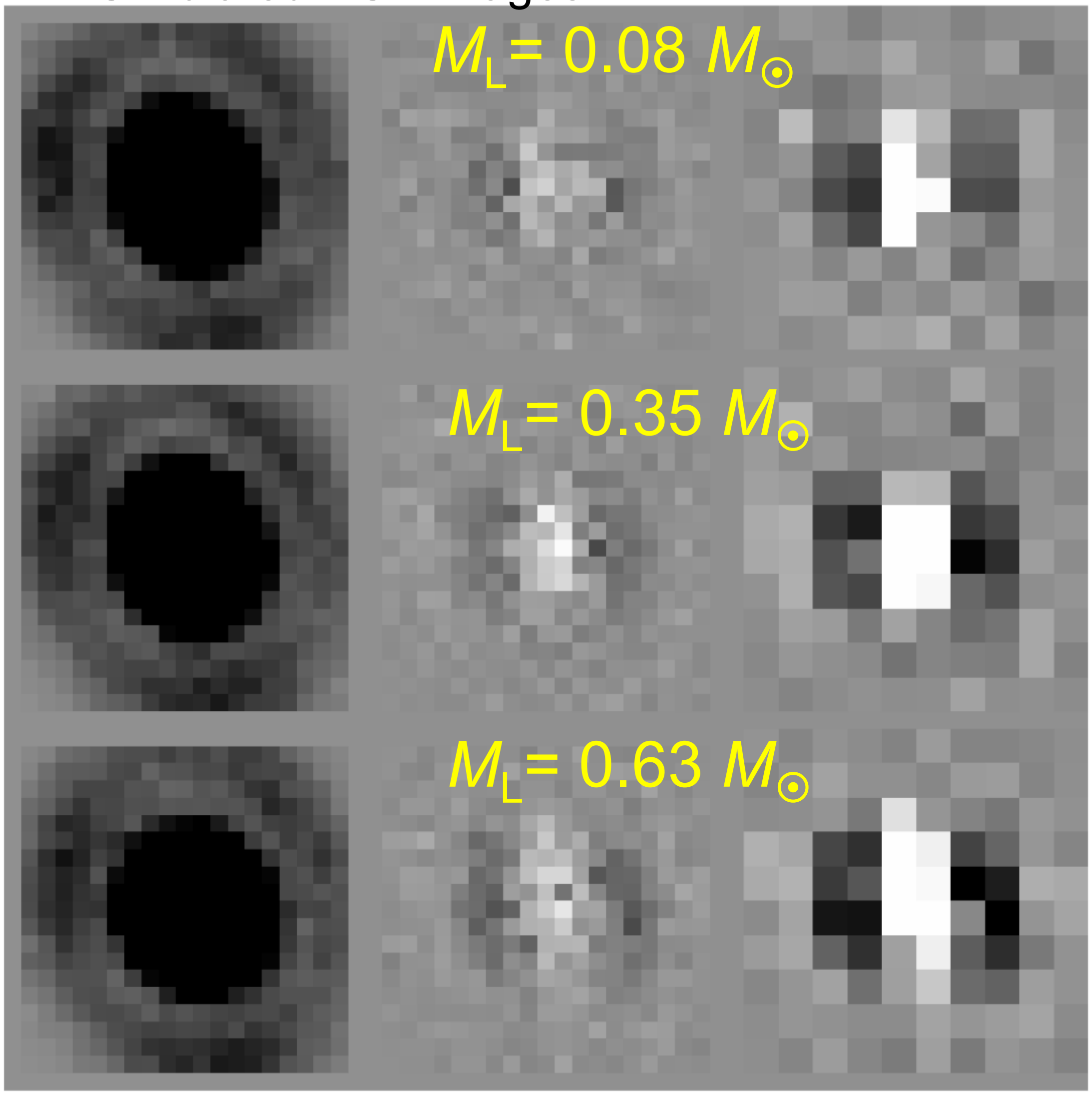


A 3× super-sampled, drizzled 4-month MPF image stack showing a lens-source blend with a separation of 0.07 pixel, is very similar to a point source (left). But with PSF subtraction, the image elongation becomes clear, indicating measurable relative proper motion.

Lens Star Identification from Space

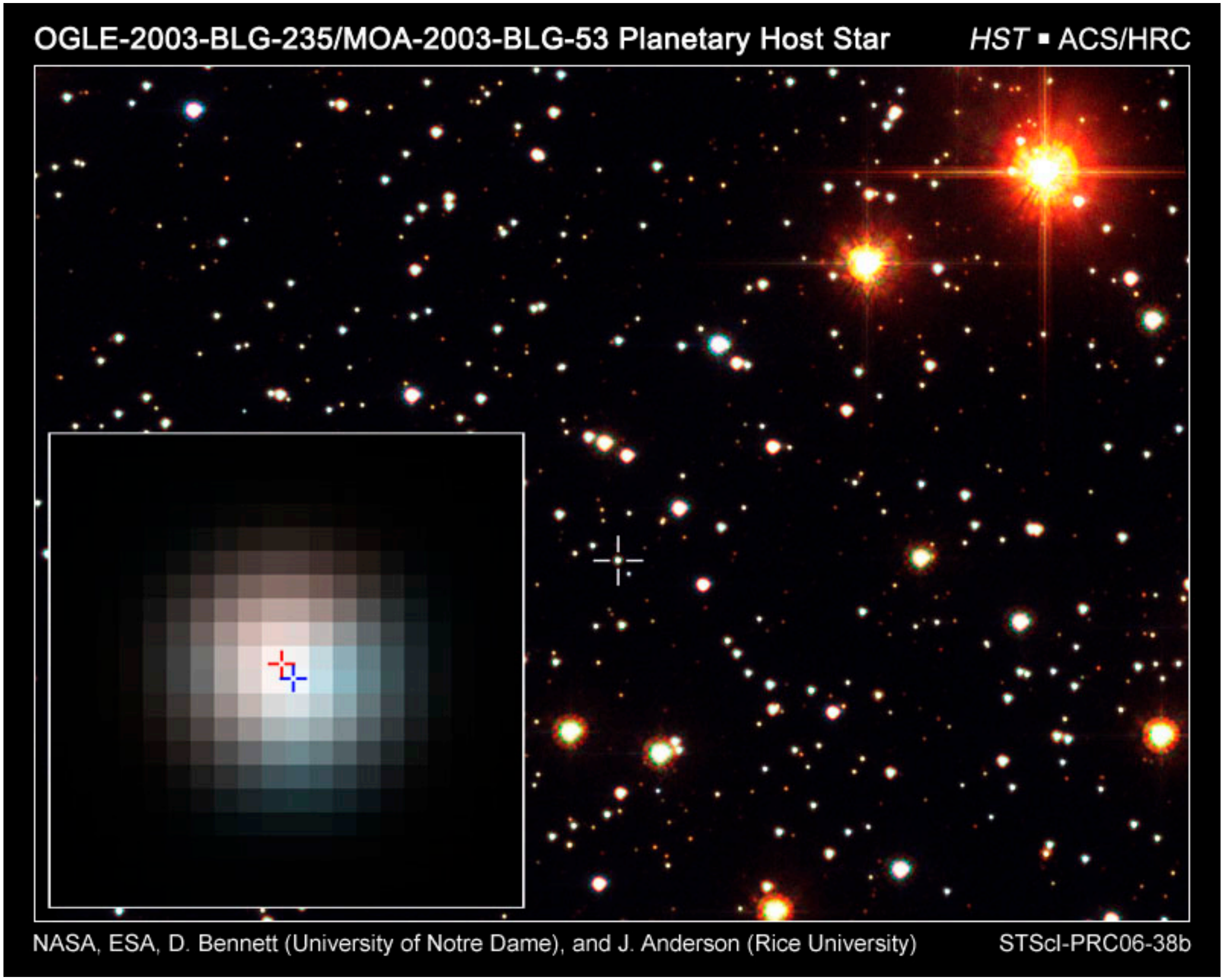
- Lens-source proper motion gives $\theta_E = \mu_{rel} t_E$
- μ_{rel}= 8.4±0.6 mas/yr for OGLE-2005-BLG-169
- Simulated HST ACS/HRC F814W (*I*-band) single orbit image “stacks” taken 2.4 years after peak magnification
  - 2× native resolution
  - also detectable with HST WFPC2/PC & NICMOS/NIC1
- Stable HST PSF allows clear detection of PSF elongation signal
- A main sequence lens of any mass is easily detected (for this event)

Simulated HST images:



raw image PSF subtracted binned

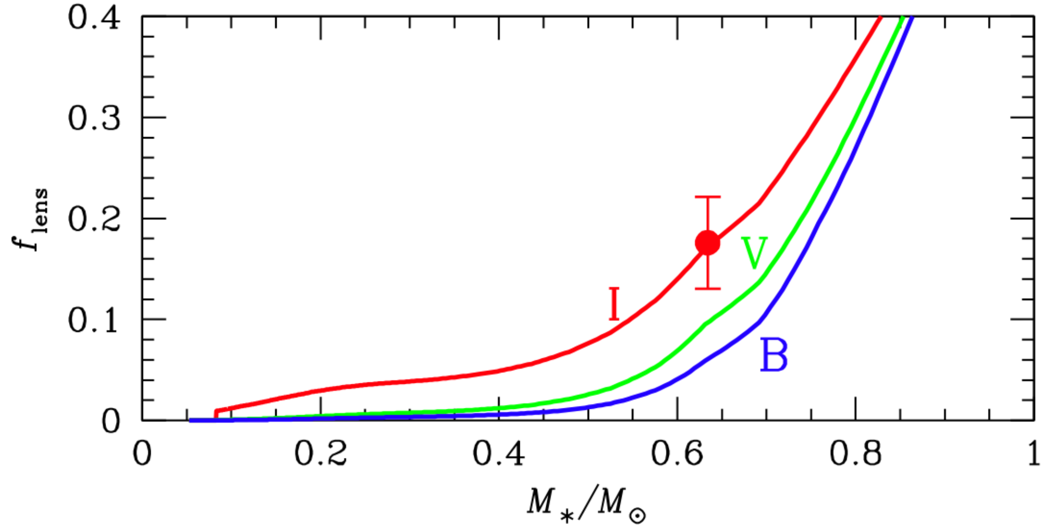
Color Dependent Image Center Shift



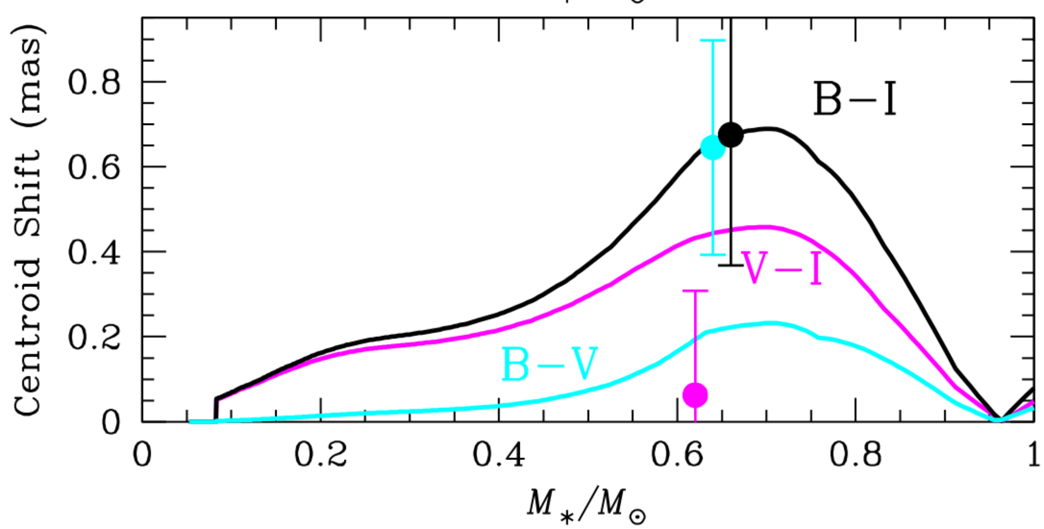
Source & Planetary Host stars usually have different colors, so lens-source separation is revealed by different centroids in different passbands

HST Observation Predictions for OGLE-2003-BLG-235L/MOA-2003-BLG-53L

Fraction of total flux due to lens star.

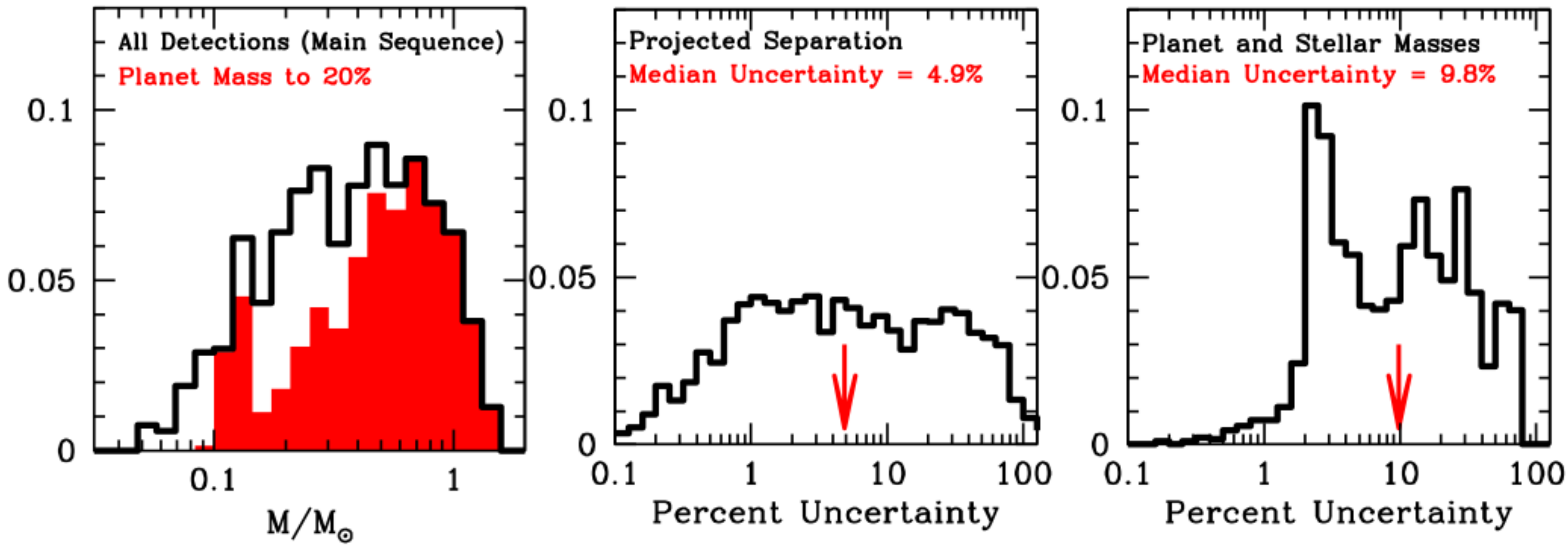


Centroid Shift between HST-ACS/ HRC passbands for follow-up images. (Units are 25 mas pixels.)



Relative proper motion μ_{rel}= 3.3±0.4 mas/yr from light curve analysis (μ_{rel}= θ_*/t_*)

Lens Detection Provides Complete Lens Solution



- The observed brightness of the lens can be combined with a mass-luminosity relation, plus the mass-distance relation that comes from the μ_{rel} measurement, to yield a complete lens solution.
- The resulting uncertainties in the absolute planet and star masses and projected separation are shown above.
- Multiple methods to determine μ_{rel} and masses (such as lens star color and microlensing parallax) imply that complications like source star binarity are not a problem.

Astro-2010 Decadal Survey

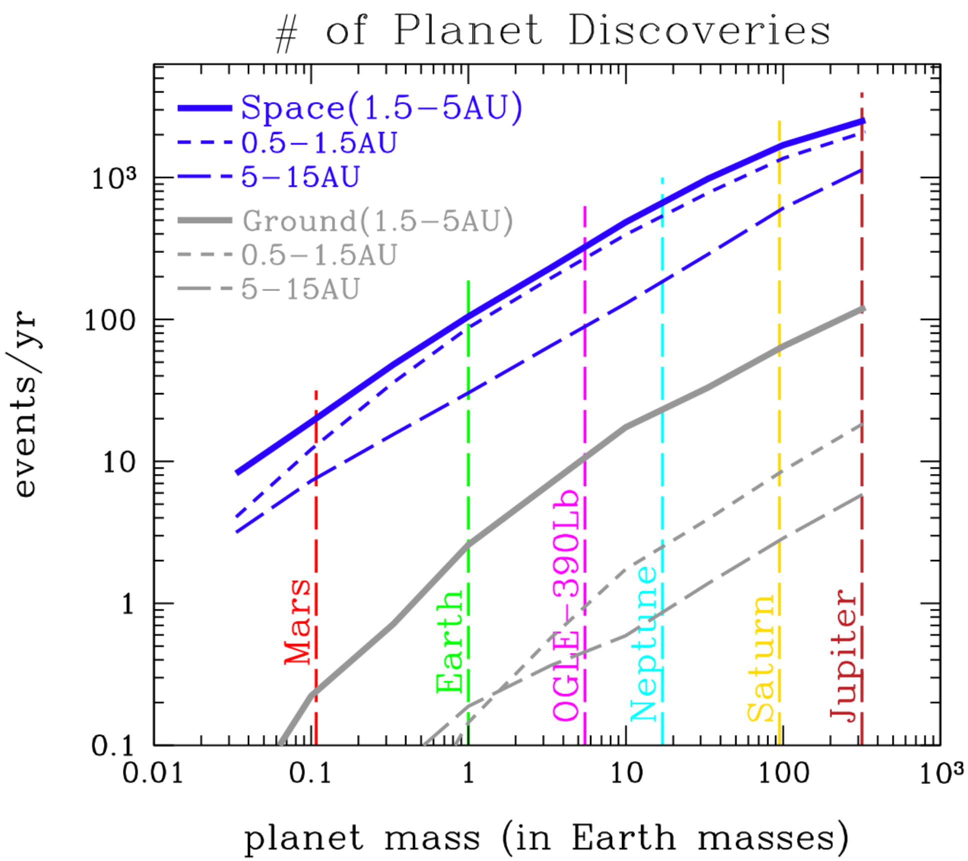
“the Kepler satellite … should be capable of detecting Earth-size planets out to almost Earth-like orbits.”

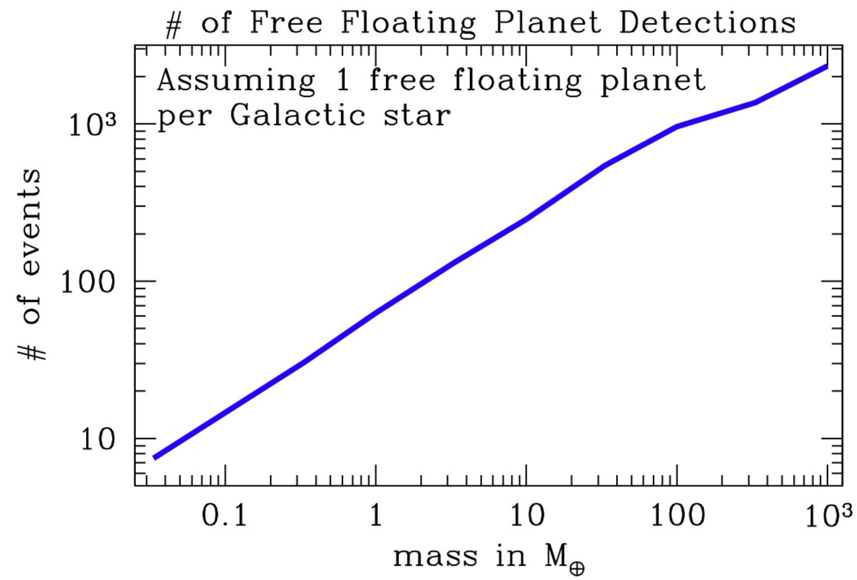
“As microlensing is sensitive to planets of all masses having orbits larger than about half of Earth’s, WFIRST would be able to complement and complete the statistical task underway with Kepler, resulting in an unbiased survey of the properties of distant planetary systems.

WFIRST does a microlensing planet search, multiple dark energy studies plus IR surveys and GO observations

JDEM-Omega is “straw man” **WFIRST** design. Concept is under development, so some details refer to the **MPF** design

WFIRST's Predicted Discoveries



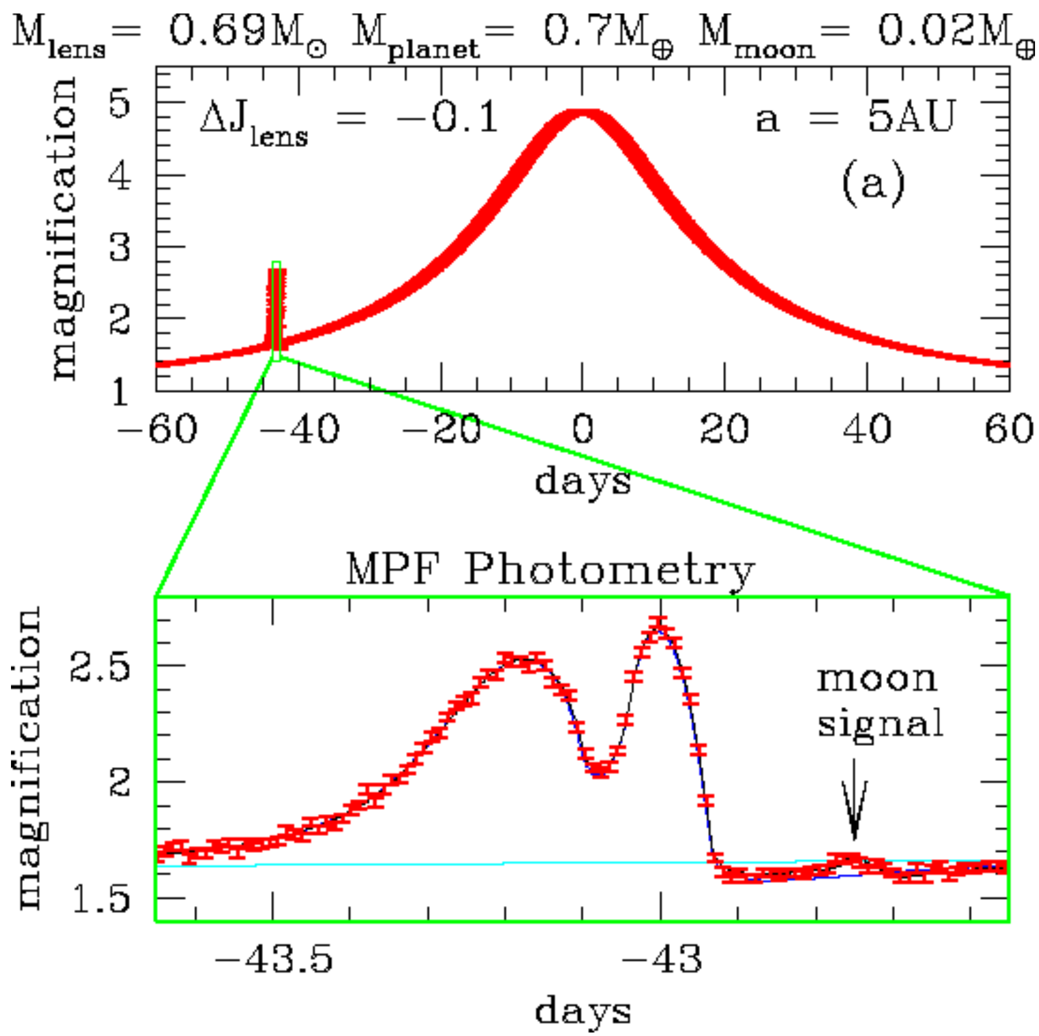


Sumi et al. 2011:
Most planets are free!

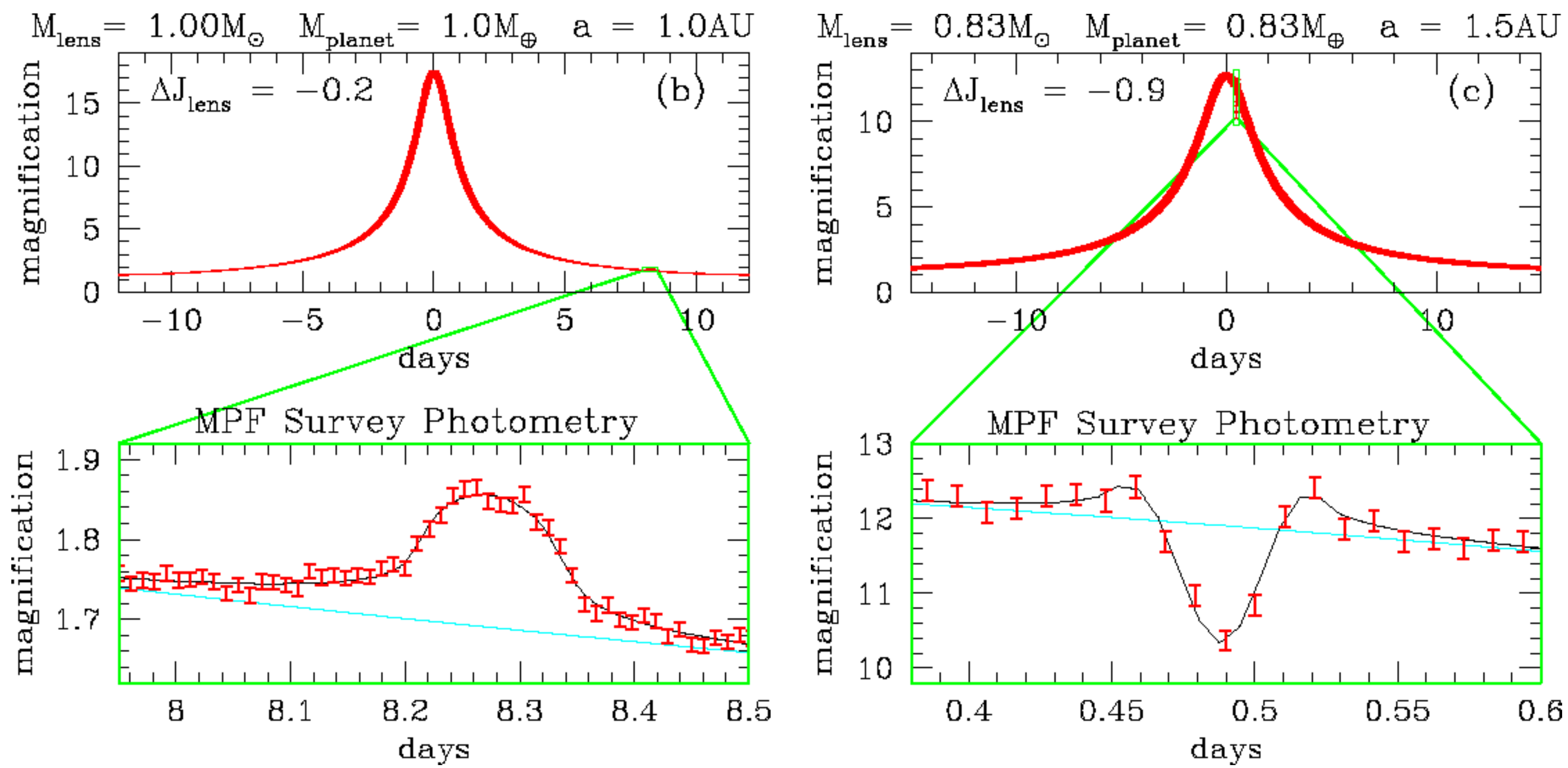
The number of expected WFIRST planet discoveries per 8-month observing season as a function of planet mass.

Simulated **WFIRST** Planetary Light Curves

- Planetary signals can be very strong
- There are a variety of light curve features to indicate the planetary mass ratio and separation
- Exposures every ~15 minutes
- The small deviation at day –42.75 is due to a moon of 1.6 lunar masses.



Simulated WFIRST Light Curves



The light curves of simulated planetary microlensing events with predicted WFIRST/MPF error bars. ΔJ_{lens} refers to the difference between the lens and source star magnitudes. The lens star is brighter for each of these events.

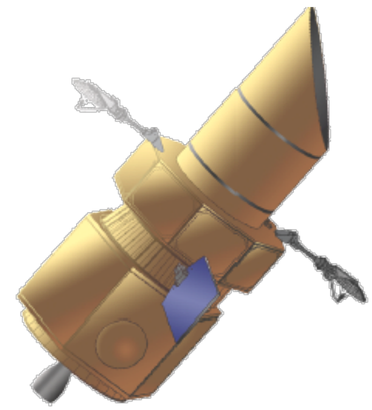
Exoplanets & Dark Energy

an old alliance

- 1999: SuperNova Anisotropy Probe (SNAP) DOE proposal
- 2000: Galactic Exoplanet Survey Telescope (GEST) Discovery
- 2001 GEST Midex proposal: 75% exoplanets 25% DE
  - Microlensing planets, weak lensing survey + supernova w/ JWST spectroscopy
  - ~Precursor to DUNE
- 2004 & 2006 : Microlensing Planet Finder (MPF)
  - 1st to use IR focal plane – 5 × more sensitive
  - DE observations during 25% of year when Galactic bulge is not visible
- 2006: DUNE proposed to CNES; NASA selects JDEM concepts: SNAP, DESTINY and ADEPT
  - Now 3 DE methods – supernovae, weak lensing, BAO

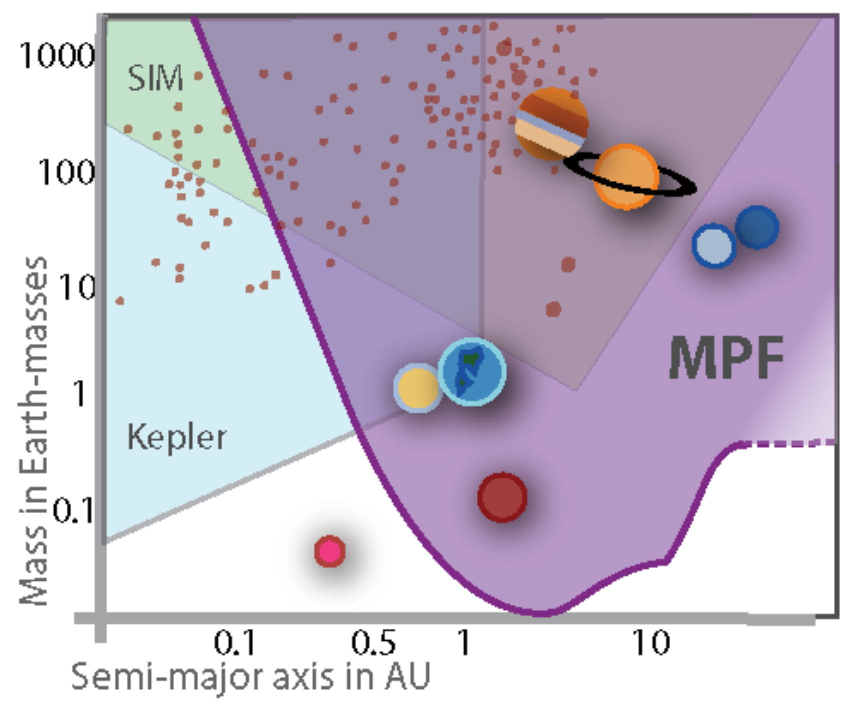
Microlensing Planet Finder

2004 & 2006 Discovery Proposals – Astro2010 submission
• 35 Hawaii 2RG HgCdTe detectors

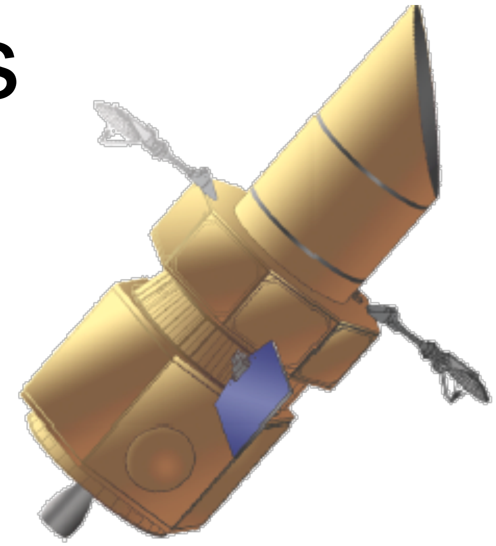


PI: David Bennett (Notre Dame)
Deputy PI: Ed Cheng (CcA)

2006 Science Team:
J. Anderson (Rice), J.-P. Beaulieu (IAP), I. Bond (Massey), M. Brown (Caltech), K. Cook (LLNL), S. Friedman (STScI), P. Garnavich (Notre Dame), S. Gaudi (CfA), R. Gilliland (STScI), A. Gould (Ohio State), K. Griest (UCSD), J. Jenkins (SETI Inst.), R. Kimble (GSFC), D. Lin (UCSC), J. Lunine (Arizona), J. Mather (GSFC), D. Minniti (Catolica), B. Paczynski (Princeton), S. Peale (UCSB), B. Rauscher (GSFC), M. Rich (UCLA), K. Sahu (STScI), M. Shao (JPL), J. Schneider (Paris Obs.), A. Udalski (Warsaw), N. Woolf (Arizona) and P. Yock (Auckland)



MPF Partners



- Goddard Space Flight Center (GSFC)
  - Project Management
  - Project Scientist Randy Kimble
  - Systems Engineering
- Conceptual Analytics
  - Hardware PI Ed Cheng
    - Led HST WFC3 and HST NICMOS Cooling System development
- Lockheed-Martin Space Systems (Domenick Tenerelli)
  - Selected through GSFC Partnership Opportunity process
  - Spitzer heritage spacecraft
  - Subcontract to ITT for telescope (Jeff Wynn)
    - Formerly space-telescope group from Kodak
    - Built back-up HST primary - without spherical aberration!
    - MPF design very similar to Next View commercial Earth-observing telescope
- Rockwell Scientific -> Teledyne Imaging Sensors (D. Gulbranson, T. Chuh)
  - Provides 35 HgCdTe detectors
  - Silicon-carbide focal plane array based on GL Scientific design (Gerry Luppino)

MPF Technical Summary

- 1.1 m TMA telescope, ~ 1.5 deg FoV, at room temperature, based on existing ITT designs and test hardware
- 35 2Kx2K HgCdTe detector chips at 140 K, based on JWST and HST/ WFC3 technology
- 0.24 arcsec pixels, and focal plane guiding
- 5 × 34 sec exposures per pointing
- SIDECAR ASICs run detectors, based on JWST work
- No shutter
- 3 filters: “clear” 600-1700nm, “visible” 600-900nm, “IR” 1300-1700nm
- 1% photometry required at J=20
- 28.5° inclined geosynchronous orbit
- Continuous viewing of Galactic bulge target (except when Sun passes across it)
- Cycling over 4 × 0.65 sq. deg. fields in 15 minute cycle
- Continuous data link, Ka band, 50 Mbits/sec

MPF Mission Design

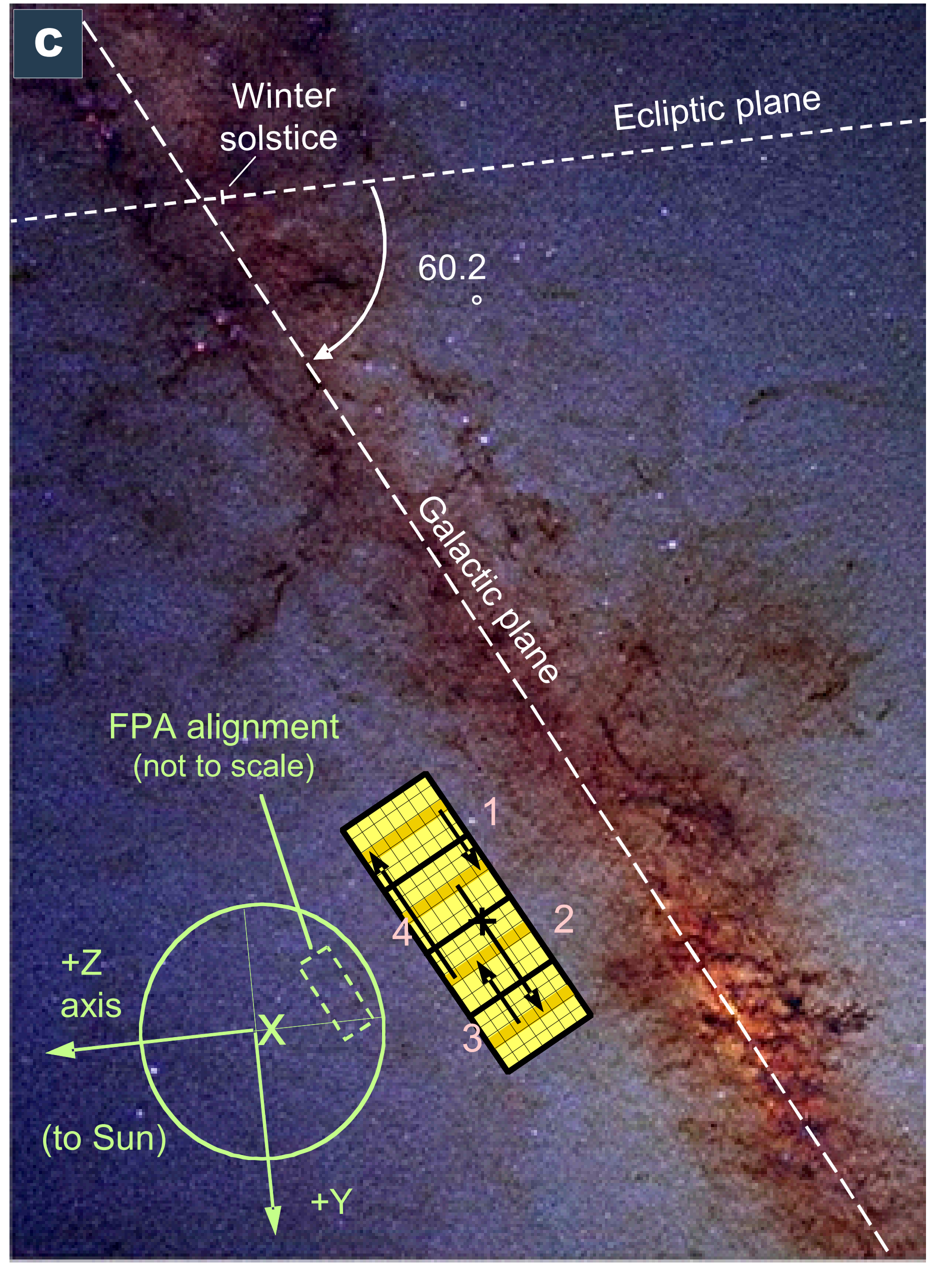
- 1.1-m aperture consisting of a three-mirror anastigmat telescope feeding a 147 Mpixel HgCdTe focal plane (35 2048^2 arrays)
- The spacecraft bus is a near-identical copy of that used for *Spitzer*.
- The telescope system very similar to NextView commercial Earth-observing telescope designs.
- Detectors developed for JWST meet MPFs requirements.
- All elements at TRL ~6 or better
- Total Cost M$ 330 (plus launch vehicle)

Property	Value	Units
Orbit	Inclined GEO 28.7	degrees
Mission Lifetime	4×9	months
Telescope Aperture	1.1	meters (diam.)
Field of View	0.95 × 0.68	degrees
Spatial Resolution	0.240	arcsec/pixel
Pointing Stability	0.048	arcsec
Focal Plane Format	146.8	Megapixels
Spectral Range	600 – 1700	nm in 3 bands
Quantum Efficiency	> 75% > 55%	900-1400 nm 700-1600 nm
Dark Current	< 1	e-/pixel/sec
Readout Noise	< 30	e-/read
Photometric Accuracy	1 or better	% at J = 20.5
Data Rate	50.1	Mbits/sec

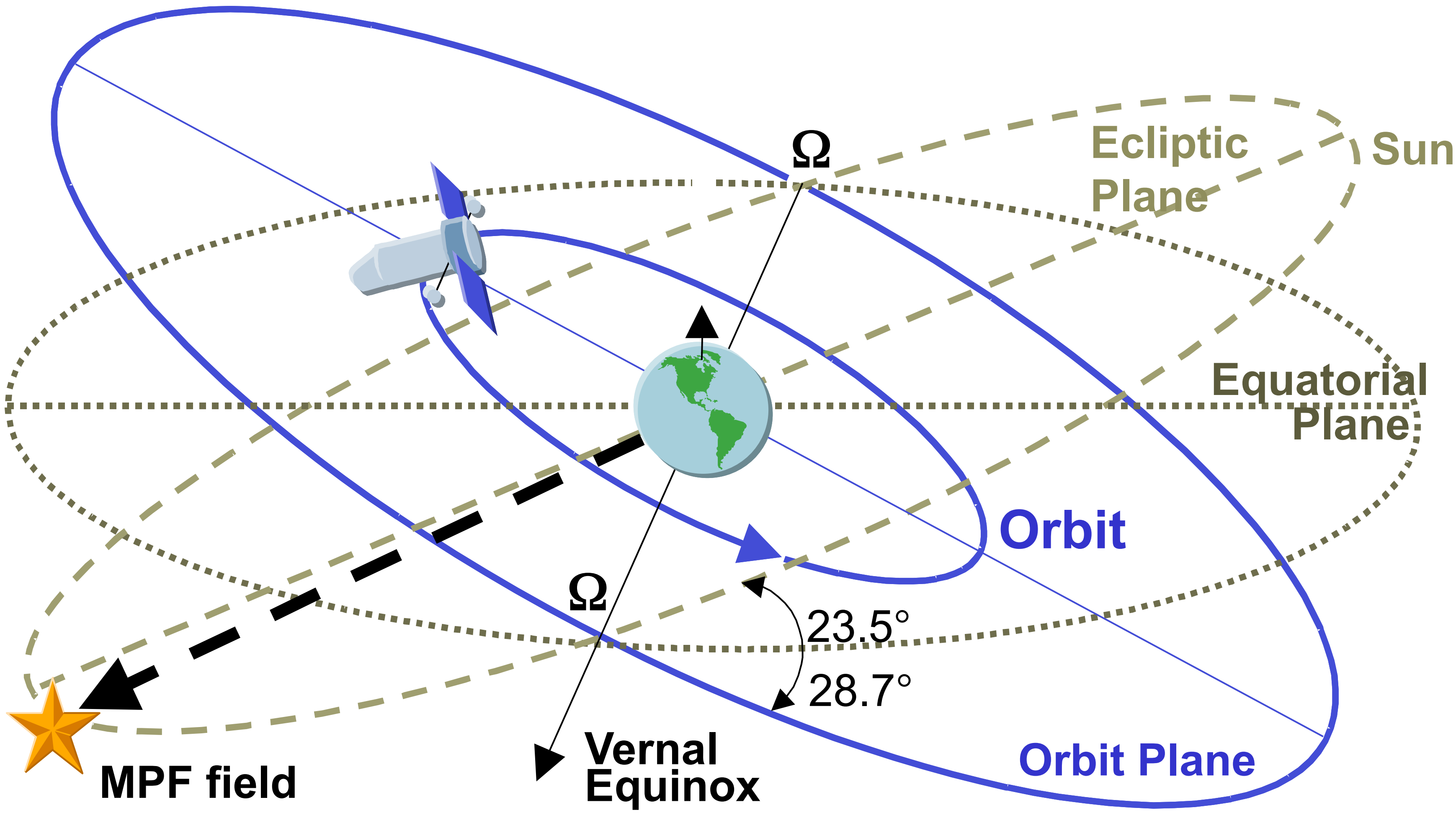
Key MPF Mission Requirements

Continuous Observations of 4 **MPF** Fields

- 1 observation of each field every 15 minutes
- Fields are oriented parallel to the Galactic plane to maximize the microlensing rate.
- Continuous 6×6 sub-pixel dither covering 2×2 pixels to confirm photometry and get best angular resolution
- Observe in “visible” and “IR” bands once every 4-8 hrs.
  - All other observations in “clear” band
- Rotate spacecraft 180 deg around LOS around June 21



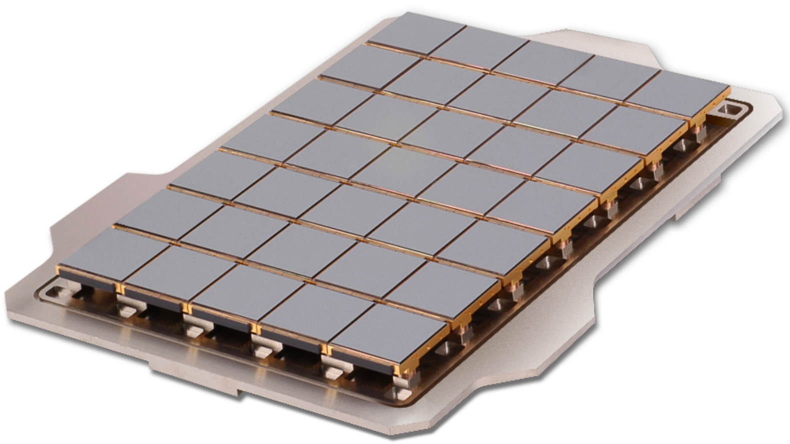
MPF in Geosynchronous Orbit



MPF's orbit allows continuous view of Galactic bulge planet search field and continuous data data downlink to a dedicated ground station in White Sands.

MPF Focal Plane Concept

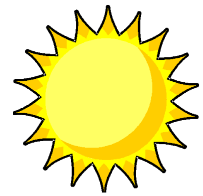
- 35 2Kx2K near IR Teledyne Imaging (formerly Rockwell) HgCdTe detectors
- one bank of 5×7 detectors
- Sidecar ASIC – Reduces wire count, produces clock signals, provides 16-bit ADC's, and digital signal processing (Fowler sampling)
- Passively cooled to 140K
- One ASIC per 5 detectors
- Each detector can watch a guide star in a sub-window while taking long exposures



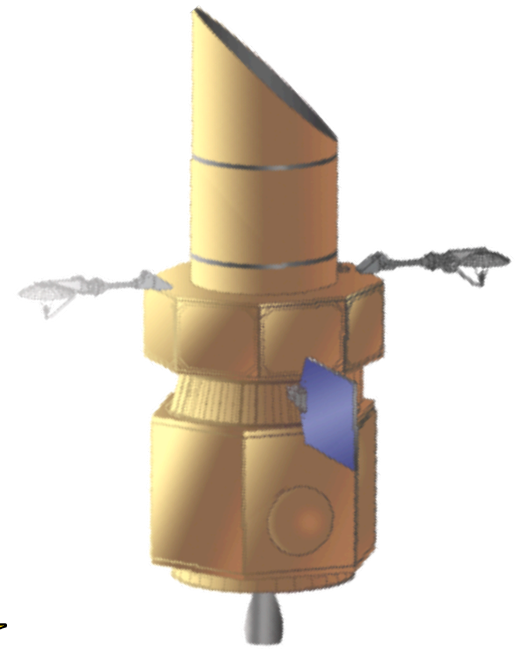
Pathfinder demonstration focal plane already built by Teledyne. A 2nd demonstration focal plane will meet mechanical specs at T = 140K during Phase A.

MPF’s Science with JDEM-Ω

- **MPF** has ½× JDEM-Ω aperture w/ 2×FOV
  - Equivalent to ½ of 4 MPF seasons

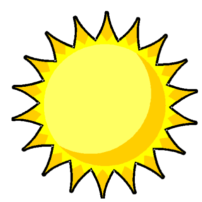


- So, yes assuming:

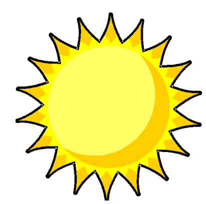


- Solar viewing angle
  - MPF: 45°-180°

- Quick slew & settle
  - JDEM-Ω needs 8 fields vs. MPF’s 4
  - Cover all fields every ~15 min



- But JDEM-Ω has:
  - Better angular resolution
  - Sensitivity to larger λ

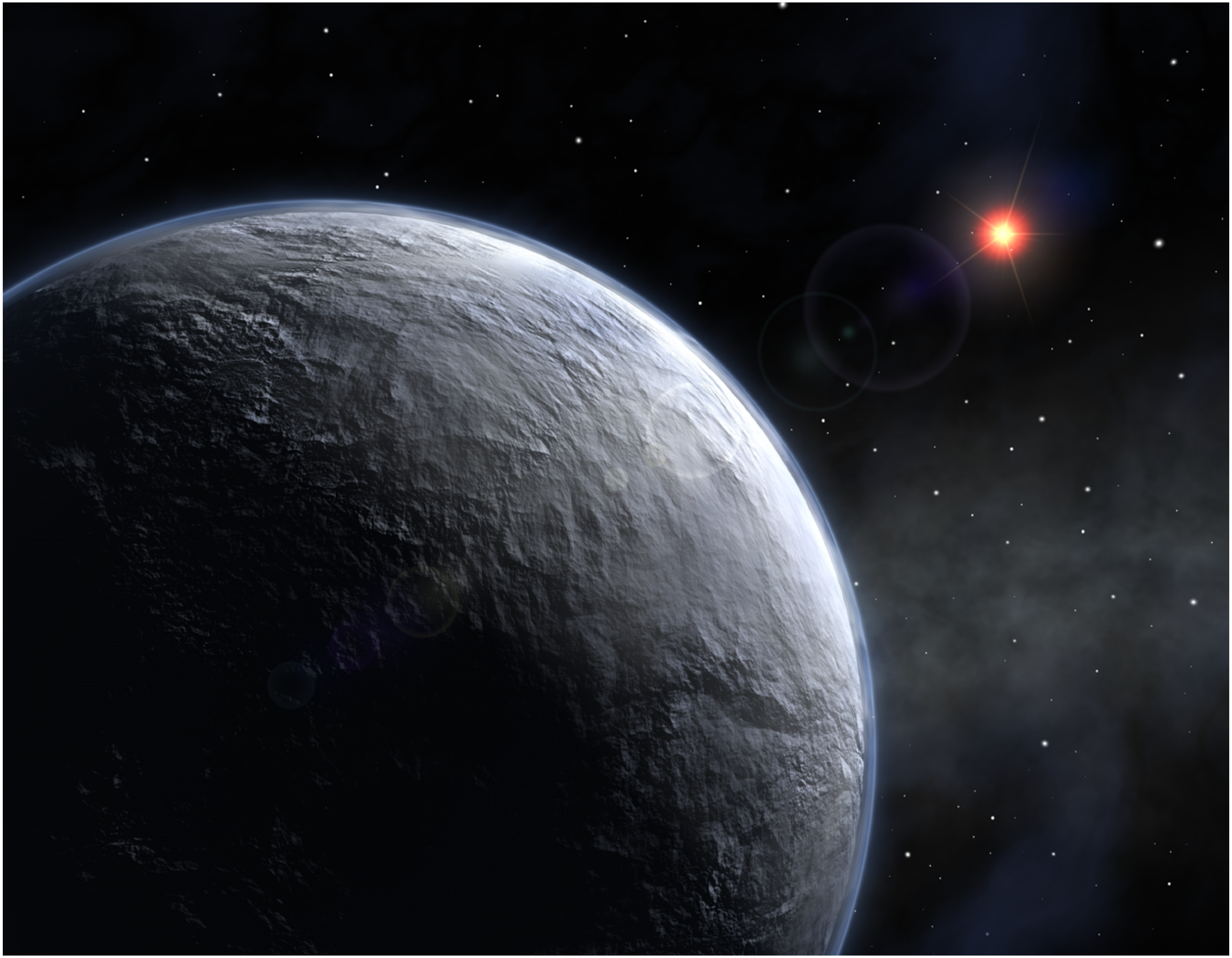


Trade Issues

- Interruptions of Continuous Observations
  - Planetary signals lost due to edge effects: hours-days
  - Microlensing Parallax mass measurements lost: months
- Early and late observations
  - Long time baseline for lens-source relative proper motion aids mass measurements
- Raw data rate: 50.1 Mbits/sec continuous
  - Co-add images
  - Send postage stamp images of selected targets
- Longer λ observations
  - Allow observations closer to the Galactic center with a higher lensing rate – but more confusion

Exoplanet Figure of Merit

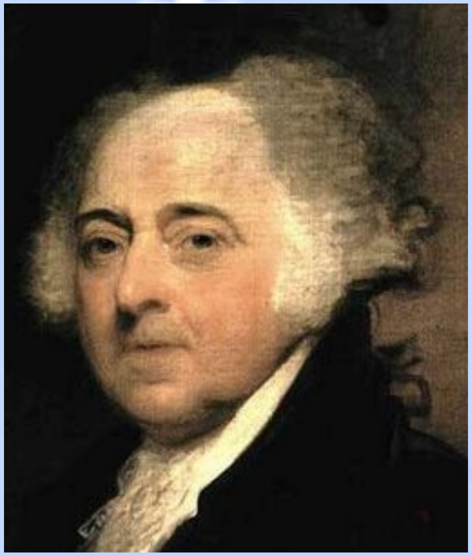
- Decadal Survey Requirements
  - Complete the survey that Kepler started
  - Help to measure $\eta_\oplus$ (fraction of stars with habitable Earth-like planets)
- MPF figure of merit
  - # of stars surveyed for Earth mass ratio planets at 1-2.5 AU
  - Guarantees planet sensitivity at a range of separations
  - This is outside the habitable zone (HZ) for most stars, but the HZ is difficult, with low S/N signals and only FGK hosts
- Requirement to determine masses and not just mass ratios needed



Economic and Political Climate

- Exoplanet Science has strong support with the US Science establishment
  - New Worlds, New Horizons decadal survey
- Exoplanet Science has strong public interest and support
  - More support than Cosmology
- But, the economy is bad and recovering slowly
- JWST is overrunning its budget
- Newly elected Republican majority in Congress
  - Seem to be planning to try and shut down the government within a few months
  - Don’t appear to have much interest in science
- So, a new case for exoplanet studies in the US is needed…

USA’s Founding Fathers on Exoplanets



John Adams: “Astronomers tell us, with good Reason, that not only all the Planets and Satellites in our own Solar System, but all the unnumbered Worlds that revolve around the Fixt stars are inhabited….”

(Urged Jefferson not to hire European Profs. for U Va. because they didn’t share these views.)

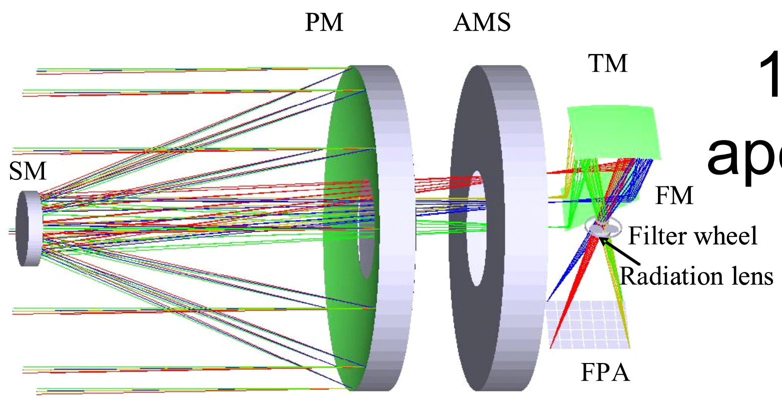
Thomas Paine: “The probability, therefore, is that each of these fixed stars is also a Sun, round which another system of worlds or planets, though to remote for us to discover, performs its revolutions, as our system of worlds does round our central Sun.”

$\eta_{\oplus}$= 1 (Adams & Payne ~1790)

Operations Requirements

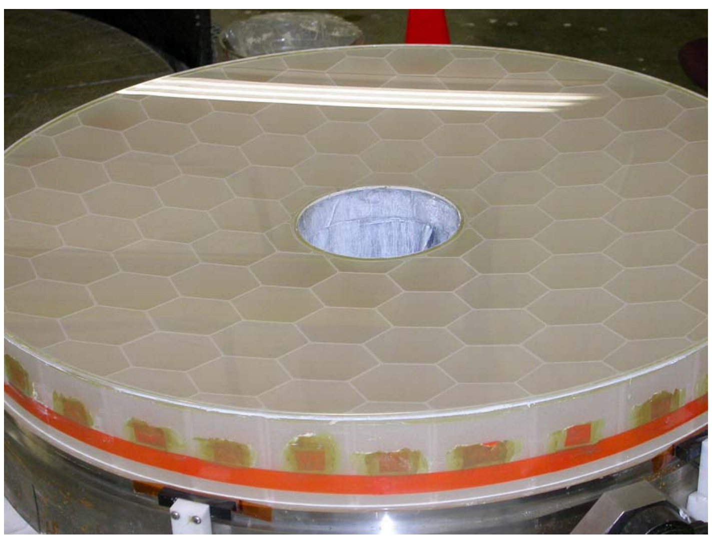
- Stare at Galactic Bulge as long as possible
  - Avoid Sun passages for 3 months around Dec. 21 - point elsewhere
- Toggle between 4 pointings on 15 min cycle
- Continuous 6×6 sub-pixel dither covering 2×2 pixels to confirm photometry and get best angular resolution
- Observe in “visible” and “IR” bands once every 4-8 hrs.
  - All other observations in “clear” band
- Occasional orbit maintenance
- Commanding, health and safety monitoring (routine after checkout)
- Data collection, archiving, processing into light curves
- Rotate spacecraft 180 deg around LOS around June 21
- Potential Moon avoidance, Earth shadow actions

MPF's Telescope (ITT)

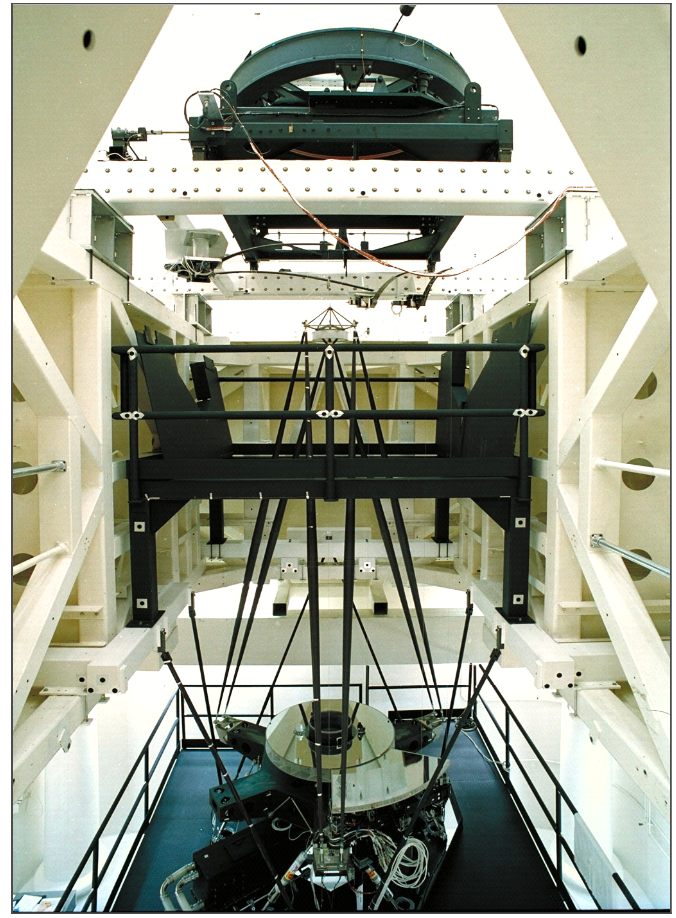


1.1m aperture

Three Mirror Anastigmatic Design based on commercial Earth observing NextView design.



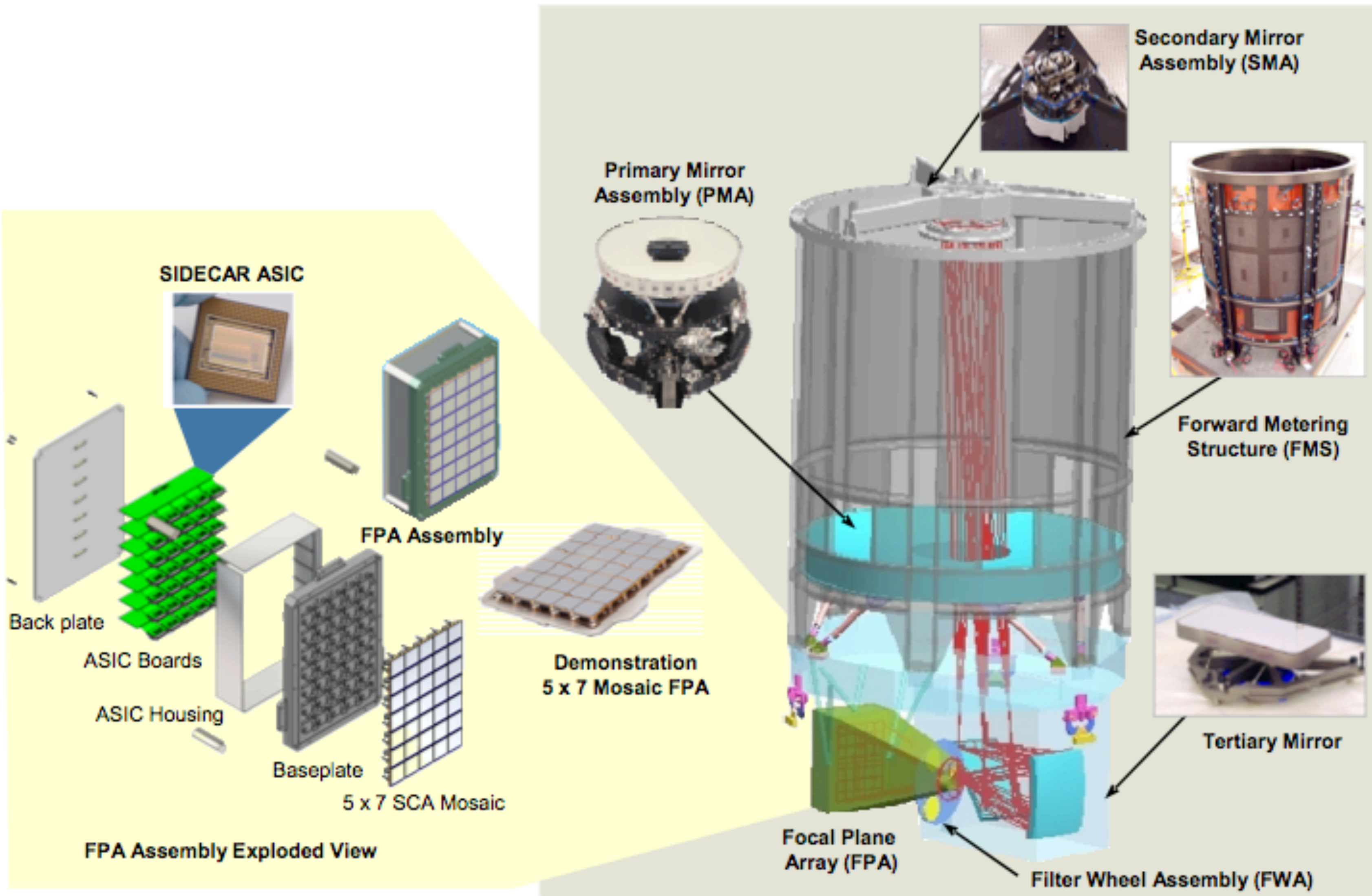
NextView Primary mirror



NextView test setup utilizing an auto-collimating flat test mirror

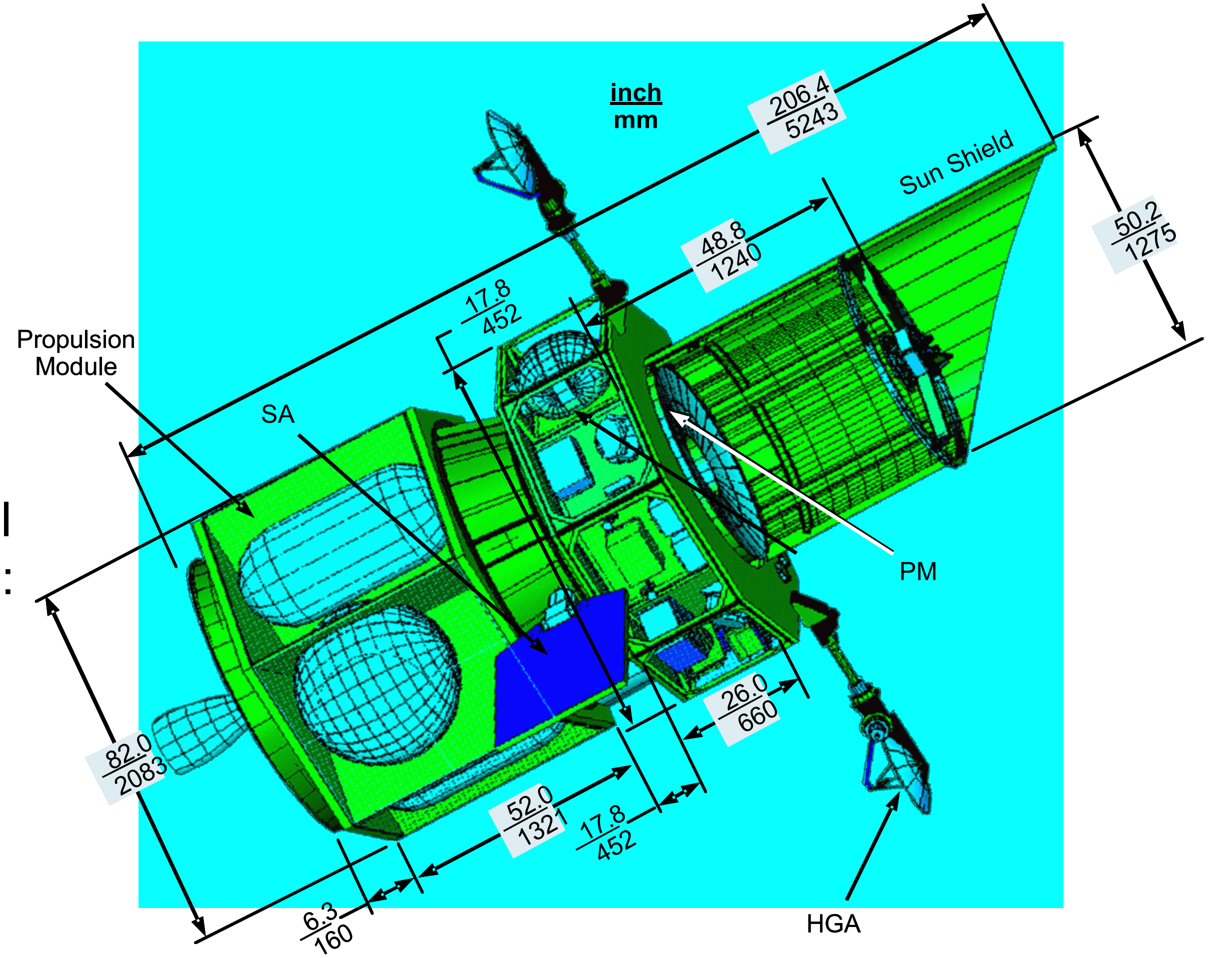
NextView test equipment can be reused for MPF - reducing cost.

MPF Telescope and Focal Plane



MPF Spacecraft

- Lockheed Martin
  - Built HST & Spitzer S/C
- High precision pointing control
  - 3-axis stabilization
  - Fine guide signal from focal plane
  - HST, Spitzer heritage
- Electronics, thermal control & Communication systems: 90% flight heritage
- Mechanisms: 100% flight heritage
- Software: 75% flight heritage, 60% direct reuse



Science Data Products

- ~ 4,000 light curves of candidate planetary lens systems, with photometry errors limited by photon noise plus at most 0.3% systematic errors, in 3 colors
- Interpreted light curves with models of star and planet masses, locations, and velocities
- ~ 50,000 transit light curves
- Archives of 100 million stellar light curves
- Raw data for further study

WFIRST Cost Reduction Ideas

- Smaller telescope (1.1m off-axis?) with more pixels
- 4k × 4k detectors?
  - Yield
  - Dynamic range
- 2× as many 2k × 2k detectors
- Start detector procurement ASAP

Microlensing Optical Depth & Rate

- Bissantz & Gerhard (2002) τ value that fits the EROS, MACHO & OGLE clump giant measurements
- Revised OGLE value is ~20% larger than shown in the plot.